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D. S. Shraiber

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ULTRASONIC DEFECTOSCOPY

by

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D. S. Shrayber

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ABSTRACT The book is intended for engineering personnel of plants, research institutes, and design offices using the defectoscopic methods or dealing with the design and production of corresponding equipment. The book also can be used as a textbook. The theoretical fundamentals of defectoscopy, the types of metallurgical defects in materials which can be detected defectoscopically, the equipment used, and the most effective defectoscopic methods are presented. English Translation: 391 pages.

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ANNOTATION

In book are described basic forms of metallurgical defects subjects to detection by methods of defectoscopy, physical base and different methods of ultrasonic defectoscopy and also associated equipment; numerous examples are given use of ultrasonic defectoscopy in industry and recommendation on its most effective application are made.

It is designed for workers for in industry practically using ultrasonic defectoscopy, it is of indubitable interest for workers of scientific research institutes and design bureaus occupied in the development of methods and creation of equipment, and can be used as an aid by students during study of a corresponding course.

Dedicated to the Fond Memory of Georgia Vladimir AKIMOV

INTRODUCTION

The book offered to the attention of the readers is an attempt of the author to expound on basis ultrasonics defectoscopy and to some measure fill the gap in native technical literature of monographs concerning this question.

In monograph are considered physical bases of ultrasonic defectoscopy and also questions connected with development of equipment and methods of control. Account is conducted basically in reference to metals, however basic propositions may be used also in inspection of articles from nonmetallic materials.

From limited volume of book author did not have possibility sufficiently in detail to consider certain essentially important questions. In those cases when this concerned questions understanding in works of other authors it was necessary to be limited limiting compressed schematic account.

This momograph is the result of work of author started in 1938 on the initiative of I. I. Sidorin and G. V. Akimov jointly with S. Ya. Sokolov, continued in laboratory conditions with group of colleagues and then at the stage of adaptation — in creative collaboration with a large collective of industrial workers.

Carrying out of this work in so wide scale to considerable degree was promoted by the constant attention and assistance on the part of A. T. Tumanov.

In the book wide use is made of separate questions on the theory of ultrasonic defectoscopy developed by the author and also results of his own investigations. Majority of these results is confirmed by practice and is used during creation of the latest equipment and composition of control methods. Certain positions can be unconditionally augmented and definitized. It is not excluded that attentive

reader, a specialist, may detect in book inaccuracies, errors and other gaps; for their indication the author will be very grateful.

Large part of experimental data given in this book is obtained in works of author with colleagues and also with workers of other institutes, designing bureaus and plants. Over several years of work on the creation and introduction of methods of ultrasonic defectoscopy, most fruitful has been collaboration with L. A. Auzin, N. V. Babkin, S. Ye. Baryshev, G. Ye. Bessonov, V. G. Blokhin, D. Ya. Bragin, B. G. Golodayev, A. G. Gorokhov, V. D. Zhukov, L. M. Zakharov, M. P. Ivanov, V. V. Kitsenko, V. A. Kozlov, V. G. Kuznetsov, A. A. Kulik, G. M. Kunyavskiy, Yu. V. Lange, A. I. Litvintsev, B. E. Lyubinskiy, Z. I. Manayeva, G. I. Misharin, A. I. Murashov, L. A. Nikitin, M. I. Paretskiy, B. V. Pevzin, G. V. Prorokov, A. M. Pyatykh, Ya. A. Rublev, A. P. Saltykov, O. T. Sil'chenko, L. M. Slepakov, V. A. Smirnov, B. A. Trubin, A. A. Tukkayev, M. P. Ural'skiy, V. P. Uftyuzhaninov, M. E. Khurgin, and Ye. A. Shifrin.

During writing of the book were considered valuable councils and remarks of S. T. Kishkin, L. D. Rozenberg, L. G. Merkulov, I. I. Teumin, Ya. M. Potak, L. P. Luzhnikov, I. N. Fridlyander, and I. N. Yermolov.

Essential help in shaping of manuscript was rendered by T. A. Borisova and A. N. Krutov.

Editing of manuscript and preparation of it for press demanded great expenditure of labor by A. K. Gruvich, Ye. N. Berlin and G. V. Popova.

To all of the named persons the author considers as his pleasant duty to express sincere gratitude.

I

DEFECTS OF METAL AND METHODS OF THEIR DETECTION

1. Influence of Defects of Metal on Strength of Machine Parts and Constructions

Contemporary machine building presents very high requirements on quality of parts and first of all on their strength, understood in a broad sense as resistance to deformation and destruction. These requirements are determined by the ever increasing intensity of conditions of work of parts. Even several decades back an overwhelming number of various machines and building constructions operated in conditions of static load at temperatures of close to room temperature and with a large reserve of strength. During design of such parts for strength on proceeded from a model of solid body possessing a complete structure, and for manufacture of them, could be used materials simple in composition (for instance carbon and low-alloy steels) distinguished by high productibility. In contemporary units considerable part of component is subjected to prolonged static loads at raised temperatures or repeated loads (including sign-alternating) at normal and raised temperatures, or works in conditions of influence on them of aggressive media of sharp thermal "shocks" radioactive radiation. For manufacture of such parts are required highly durable, heat-resisting, acid-resistant, metallic and nonmetallic materials (steel alloys, plastics, possessing improved special characteristics) with maximum strength, prolonged durability, minimum creep, maximum radiation tolerance, resistance to thermal fatigue, corrosion resistance, etc.

Steels and alloys satisfying these requirements as a rule have a complex composition and are characterized by lower technological properties which hampers

manufacture from them of parts by means of plastic deformation and in a number of cases leads to necessity of creation of new technological processes for producing articles of necessary form and properties.

Requirement of combination of above-indicated properties with small weight of article leads also to application of compound constructions, for instance constituting composition from metallic and nonmetallic materials united by means of bonding or soldering.

Methods of calculation on strength of parts working in complicated conditions of load, is considerably more complicated, especially when designing component for aviation and rocket technology inasmuch as in these cases the designer, seeking maximum reduction in weight, departs from minimum reserve of strength.

For instance for basic component of aircraft engines (crankshaft, connecting rod, blade and disk of turbine and compressor) minimum safety factor is 1.3-1.5 [1] whereas in the common machine building and in building practice it reaches to 10-15.

Development of a study of strength, especially theory of elasticity, plasticity, creep and fatigue, accumulation of large experimental material in these regions allowed considerably improvement in methods of calculation of component strength. On the basis of application of improved methods of calculation and use of highly durable materials can be carried out, for instance, aviation and calculation designs distinguished by their low "specific gravity" and high compactness. Such constructions are characterized by complexity of conditions of load of parts, in particular working in conditions of uniform state of strain at which influence of localized zones with lowered properties (observed as a result of scattering of properties, characteristic for alloys of complicated composition) on lowering of strength charecteristics appears especially sharply.

In these conditions even the most complicated and exact methods of calculation cannot anticipate all possible causes of lowering of strength and do not guarantee reliability.

Here the character of destruction of constructions, working in specially complicated conditions of load (for instance, aviation and rocket) and consequences caused by them, essentially differ from character of destruction of constructions working in less stringent conditions.

Thus, breaking of rod of powerful press (Fig. 1)[1] occurring under action of repeated static loads leads to breakdown of expensive equipment and associated economic loss. Destruction of head of railroad rail (Fig. 2) can lead to catastrophe. However fatigue character of break of rails testifies to the fact that crack leading to destruction was developed gradually and with correct organization of control of state of the track could in good time be revealed and catastrophe prevented.

Still more complicated case is represented in Fig. 3: accident of axial-flow compressor of turbojet motor of aircraft occurring from break of one of blades. To prevent such an accident is naturally considerably more complicated since destruction occurs not on a surface accessible for inspection as in the case of breaking of a rail. Finally, in Fig. 4 is shown destruction of a spherical vessel welded from sheet steel in process of test of it under internal air pressure equal to 90% of calculated value. This case one should consider as destruction of a system with high compliance [2] and consequently with large reserve of elastic energy. Various aviation and rocket constructions form such systems. As is known, local porcess of deformation or formation of a crack in yielding systems can lead to destruction to having character of an explosion and consequently to unavoidable catastrophe. Apparently this explains the well-known cases, occurring in 1954, of catastrophes of English aircraft "Comet". Cabins of these aircraft by volume were near 140 m^3 and at a height of 10 km were under an internal excess pressure near 0.6 atm. In these conditions a small fatigue crack in sheathing of upper part fuselage (at the opening under antenna of radio direction finder) turned out to be sufficient to cause explosive destruction of the midportion of the fuselage.

Investigations of ruptured component permit making conclusion concerning the fact that along with errors in calculations or technology of manufacture of components (for instance "severing" or incorrect orientation of fiber) during plastic deformation of blanks (see Figs. 5 and 9) causes of breaking frequently can be various kinds of defects present in metal lowering its strength characteristics (all cases of destructions shown in Figs. 1-4 are explained by

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[1]Figs. 1-76 are placed on insert between pages 12 and 31.

presence of such defects.

Metallurigical defects constitute imperfection of structure of metal appearing on different stages of technological process and differently affecting strength of parts depending upon their load conditions in exploitation. Nature and magnitude of metallurigical defects is extremely diverse.

As is known [6] theoretical values of strength of metal calculated on magnitude of energy expended on formation of two new surfaces during surmounting interatomic bonds in ideal grid of single crystal [7] is many times higher than values of "technical" strength obtained during test of real samples of the same metal. Thus, for iron theoretical value of strength exceeds 1000[1] kg/mm^2, and "technical" ~25 kg/mm^2. This divergence is explained by presence of various kinds of defects, imperfections of structure of crystal body, influence of which on properties of this body is so considerable that contemporary solid state physics is frequently defined as the physics of defects. Such defects (imperfections of fine structure) include, first of all, dislocations, i.e., individual zones of distortions of atomic grid, contained in real crystals in huge quantities (order 10^8 per 1 cm^2).

Theories of dislocations, bases of which were laid in the thirties by Taylor, Orowan and Polany [8, 9, 10] explaining the mechanism of plastic deformation of metal were for long time a subject of discussion. In recent years as a result of investigation of fine structure of crystals by special methods of phase-contrastive and electron microscopy success has been had [11, 12] in observing dislocation (Fig. 8) and establishing the fact that strength sharply increases both with a complete absence of dislocations and also when they are sufficiently large in number.

Defects of rougher order are submicroscopic cracks by dimensions not exceeding limit of resolution of optical microscope ($\leq$0.2 μm), on the edges of which occurs a sharp concentration of stresses. Such cracks, according to the hypothesis of Griffith [14] can be formed along boundaries of blocks of a crystal in process of its growth and also, as shows Ya. I. Frenkel' can appear as a result of application of stresses [15, 16].

[1]Such values of strength can be obtained on specially prepared finest filiform crystals [13].

Contemporary electron microscope permits observing submicroscopic cracks, confirming this hypothesis. In Fig. 6 is given electron photomicrograph of fine structure of pure aluminum after hot pressing obtained by author and Ye. K. Molchanovoa [17]. Distinctly seen is a conspicuous crack formed on boundary of blocks of mosaic structure of the crystal.

Note the coincidence of form of opposite edges of crack in center of photograph and also that angles between margins of crack and ribs of branch of dendrite are equal. Apparently birttle rupture occured here. In order to check this proposition the photograph cut along the upper margin of the crack proceeding from center to the right upwards; then upper part of photograph displaced clockwise on angle α. In this case the rib of the upper part of branch of dendrite coincided with the rib of the lower and margin of crack in center ideally were closed. Such coincidence evidences brittle rupture in this place (breakaway). Crack proceeding to the right — upwards was closed not completely, apparently in this place took place plastic deformation concluded by viscous destruction.

Brittle rupture in so close relationship with viscous in such a high-plastic metal as pure aluminum, even under conditions of comparatively "soft" state of strain indicates that what even so high plasticity of metal is no guarantee against the appearance cf fragile submicrocracks. This shows that submicrocracks in some number apparently always occur in real metal. Submicrocracks are formed also on the surface of a crystal. Removal of surface layer, rich in cracks permitted A. F. Ioffe [18] to increase strength of rock salt crystal hundreds of times and to obtain a value close to theoretical.

In real metal — a polycrystalline body — still rougher defects are met, for instance, microscopic cracks of dimensions >0.2 μm. Such cracks are formed on surface of steel parts in the process of their machining[1] or exploitation.

In spite of the insignificant (order of several μm) depth these cracks (Fig. 7), as it was shown in the works of Ya. M. Potak [19] and also S. T. Kishkin and others [20], sharply lower the strength of a part (especially during operation in conditions of complicated state of strain or influence of superficially active media), accelerating its destruction (Fig. 10). Removal of damaged surface layer

[1]These cracks can appear, for instance, during unfavorable conditions of grinding when tensile residual stresses on surface of article attain magnitude of resistance to destruction of material.

by mechanical means (stripping by thin sandpaper, sand blasting) or by means of electrolytic dissolution essentially increases strength of part.

Finally the roughest are macroscopic, defects, visible in a number of cases by the naked eye, and constituting various kinds of disturbance of continuity or uniformity of the metal. These defects can become the cause of an especially sharp lowering of strength of a part and its destruction (see Figs. 11-13) [3, 21]. With increase of dimensions of part probability of presence of defects increases, therefore real lowering of strength on parts with large dimensions appears sharper (scale factor).

Variety of nature of defects met in metals and also their different influence on properties of metals leads to certain conventionality in the actual determination of the concept of a defect.[1] Defects in the applied technical understanding of this word should be considered as those deviations from normal quality foreseen by technical conditions, which worsen working characteristics of metal or a part and lead to lowering of high quality or discarding. Not any defect of the metal is a defect of the part — deviations from normal quality of metal which are not essential for work of a given part, should not be considered as defects of it. Moreover, deviations, which are defects for parts working in some conditions (for instance, in conditions of fatigue load) can not be defects for other conditions (for instance, statically loaded conditions).

The struggle for improvement of operating characteristics of metal and parts rationally prepared from it reduces to the complete exclusion of the most dangerous defects and lowering to a certain minimum of defects which present a smaller danger in concrete conditions of exploitation of a given part. It is natural that the level of "safe minimum", determining quality of a part, is a function of intensity of conditions of work of the part and drops with increase of this intensity.

High quality of metal and parts made from it can be ensured by improvement of technology (with the purpose of excluding possibility of appearance of defects), and also methods of quality control (with the purpose of revealing defects and rejecting defective stock, half-finished products, parts).

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[1]For instance, during manufacture of semiconductor elements from germanium or silicon a defect is considered to be the presence of impurity in the amount of one atom per 10^{10} atoms of germanium or 10^{13} atoms of silicon.

Degree of combination of shown directions should be determined by concrete conditions. Frequently the most reliable radical solution of a problem is transition to new technology. Thus it turned out to be that practically it is impossible to reveal thin oxidized scales in the cast articles from multicomponent nickel alloys. Translation of these alloys to vacuum melt made it possible to exclude the possibility of formation of oxidized scales, and to increase considerably the exploitational strength of articles. Necessity of development of special methods of control dropped.

Quality control of important constructions whose parts are designed with a minimum safety factor and are subjected in their work to very considerable loads should be carried out very thoroughly. Sample control (test of samples taken from a portion of parts), applied usually for production of little importance is impossible to consider sufficient, since this does not permit judging quality of the totality, i.e., absence of defects in every part. Only one hundred-percent control of half-finished products and ready parts can give reliable results. It is clear that for such control can be applied only nondestructive methods.

Nondestructive methods of quality control of materials can be based on different physical principals. These methods are not universal and have different fields of application. Every method can be used for the detection of only specific defects under the observance of certain limiting conditions.

To solve the most complicated problems connected with control of important parts, one should apply a complex of different methods.

Rational use of a complex of nondestructive methods of control permits increasing reliability and quality of production, prevents breakdown of complicated units, and gives to production huge economic advantages. This helps also to master production of new complicated alloys and also to introduce new progressive technological processes. One-hundred percent nondestructive control permits determining quality of materials or half-finished products, checking effectiveness of improvement of industrial process, and makes it possible to remove a suitable part of production for further treatment. Systematic carrying out of nondestructive tests on different stages of technological process and statistical treatment of results of these tests permit determining on what stages of process appear defects, and consequently establishing and removing causes of

defects. The actual essence of control operations changes. A passive method, only fixing the quality of ready parts does control becomes an active method of correction of a technological process. The active role of control in conditions of production automation especially increases.

Thus, with rational use of nondestructive methods of control they can become an effective means of improvement of a technological process.

Control operations constitute an inalienable and equally justified link of the technological process. However, if methods of nondestructive control are applied without taking into account their real possibilities, and outside limits of their optimum use, the effect of their application can be negative. So that this does not happen, it is necessary to study in detail articles subject to control, character of deflects appearing in them, and also physical bases and possibilities of nondestructive methods of control.

2. Technology and Defects of Metal

Contemporary technology anticipates obtaining from metals alloys with required properties and the production from these alloys of articles possessing needed form and dimensions.

The basic method of preparation of alloys is the mixing of different metals in specific numerical ratios, melting and casting them in special forms.[1] Here castings of different configuration can be obtained, requiring only insignificant mechanical and heat treatment to transform them into ready articles.

Improvement of foundry technology at present permits obtaining from special foundry alloys almost-ready articles of complicated form (precision casting) or manufactured articles and half-finished products with improved structure and with raised methcnical properties (centrifugal casting, cast wire and ingots obtained by the method of continuous casting, cast sheets from cast iron, etc.).

To manufacture important parts in most cases methods of pressure treatment of metals are used. For this from special alloys in the beginning a blank of simple

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[1]Recently a very long-term method of powder metallurgy has been developed, consisting in mixing hard powders of metals with each other or with nonmetals, or with different compounds of metals and nonmetals, in pressing these mixtures and sintering them. By this method different articles can be prepared, including refractory metals, without heating them to the melting point. Subsequently we will consider mainly technology which provides fusion and casting of alloys.

form is cast (parallelepiped cylinder) — an ingot which there is subjected to hot and cold pressure treatment: rolling, pressing, forging, stamping, drawing. During pressure treatment structure of alloy improves, certain defects of ingot "are healed" (welded) and strength characteristics considerably increase.

Strengthening occurs, however, only along direction of power flow. "Transverse" mechanical properties worsen, and in certain cases can be even lower than for the cast alloy.

Half-finished products obtained after pressure treatment of ingot are subjected to different thermal, chemical-thermal, electrochemical treatment and to machining.

Deviations in conditions of technological process lead to appearance of different defects [22, 23, 24, 25, 26, 27].

Macrodefects found in metallic articles and intermediate products are distinguished in dimensions, location, nature and origin.

They can appear on different stages of manufacture, in the process of fusion and casting, pressure treatment, thermal treatment, chemical-thermal treatment, and electrochemical treatments, machining, correction and assembling combining metals (welding, riveting, soldering, gluing).

Besides, defects in half-finished products and ready articles can appear in conditions of storage, transportation and exploitation.

1. Local (different disturbances of continuity — pores, gas cavities, cracks, stratification, flocs, impediments, settings, and others). Local defects localized in limited volume can be point, linear, plane and volume. According to location they are divided into external (surface and subsurface) and internal (depth).

2. Distributed in limited zones (liquational accumulations, zone of incomplete hardening, corrosional injury, and cold hardening).

3. Distributed all over volume of part or along its surface (general inadequacy of chemical composition, structure, quality of machining).

Depending upon form, dimensions and orientation relative to effective stresses, defects can be sharp and blurry concentrators of stresses.

Let us consider briefly features of basic defects met in metallic blanks, half-finished products, and articles in their technological treatment, storage, transportation and exploitation.

Fig. 1. Rod of powerful press, destroyed during exploitation [21].

Fig. 2. Railroad rail, destroyed during exploitation.

Fig. 3. Compressor of turbojet engine, destroyed during exploitation.

Fig. 4. Destruction of welded spherical vessel during pneumatic tests.

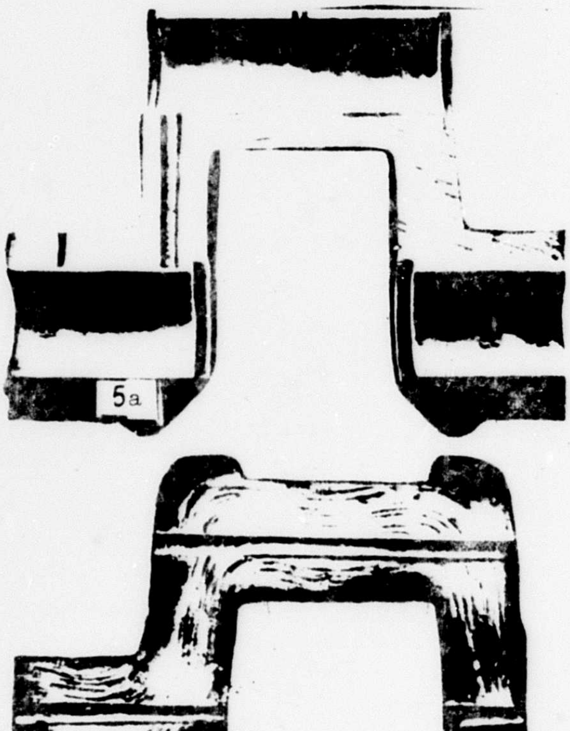

Fig. 5. Crankshaft, prepared incorrectly — a, and correctly — b.

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Fig. 6. Submicroscopic crack in aluminum. Electron photomicrograph ×15000 [17].

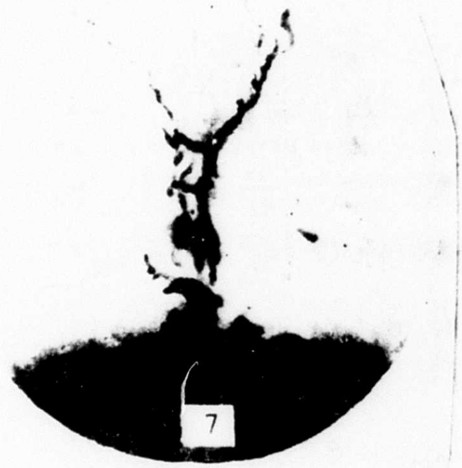

Fig. 7. Microcracks on surface of hardened steel part. ×1200 [19].

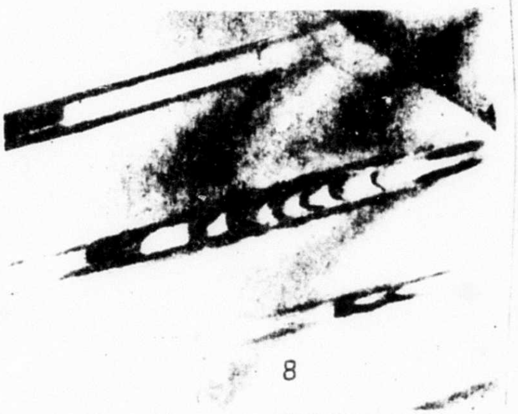

Fig. 8. Dislocations in stainless steel. Electron photomicrograph. ×6000 [11].

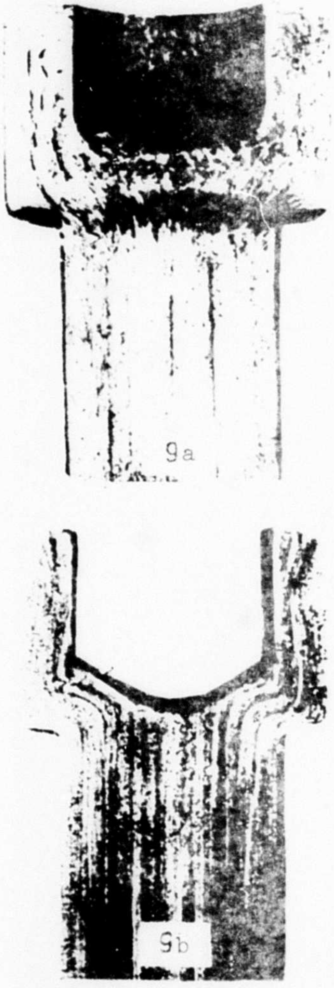

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Fig. 9. Blank of special bolt, prepared incorrectly – a and correctly – b.

Fig. 10. Crack revealed in a part in the initial stage of exploitation – a and after 30 h – b. ×200.

Fig. 11. Hook on the safety belt of a steeplejack, destroyed in exploitation due to rough defect — large cavity. ×0.5 [21].

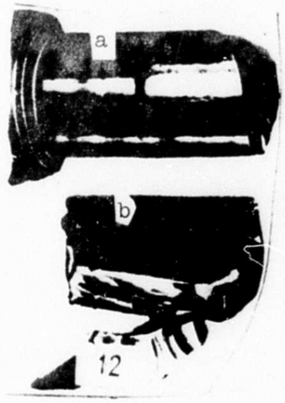


Fig. 12. Destruction of crankshaft starting at site of non-metallic occlusions: a — overall view, b — break.

Fig. 13. Connecting rods of an aircraft engine, destroyed in exploitation due to presence of hairline cracks on internal surface of head.

Fig. 14. Nonmetallic occlusions in a forging from aluminum alloys. X200

Fig. 15. Slang occlusions in wrought iron. X130 [21]

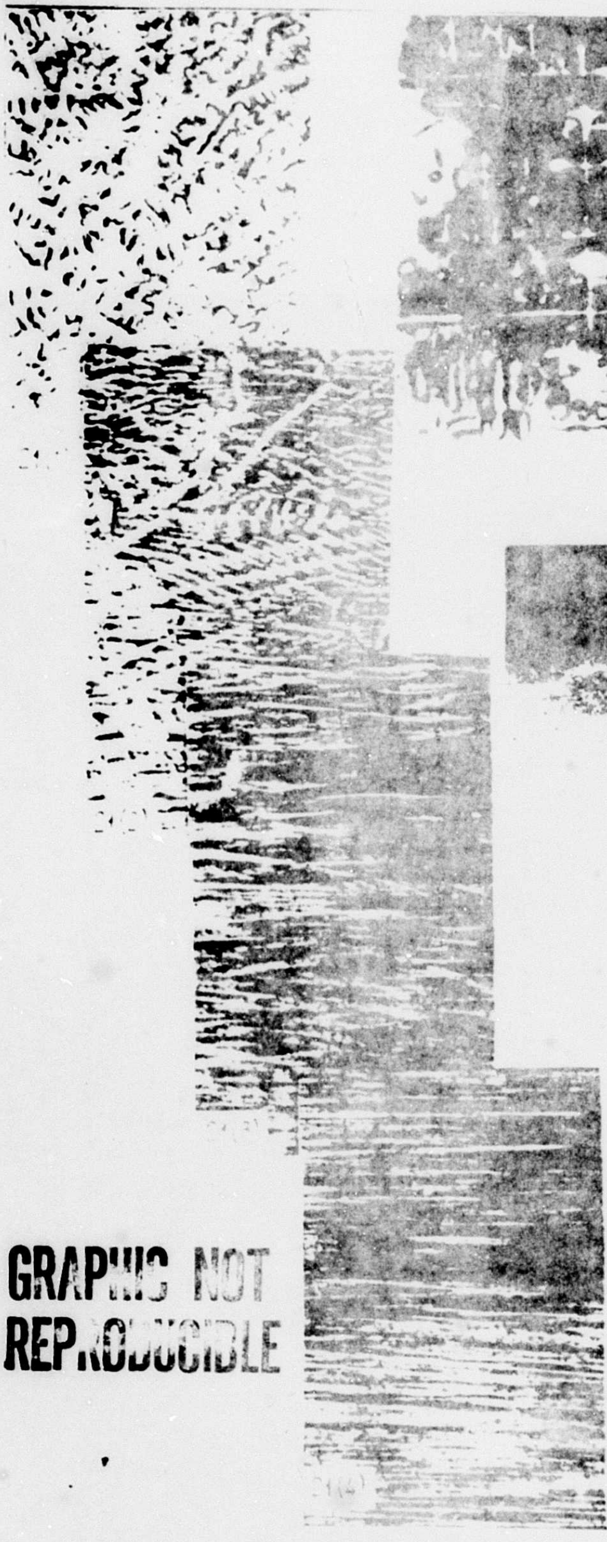
Fig. 16. Oxidized scale in plate from aluminum alloy. X1

Fig. 17. Nonblended regions in a billet from aluminum alloy X1

Fig. 18. Shrinkage cavity in ingot. X0.1 [25]

Fig. 19. Shrinkage porosity in wrought iron. X100 [21]

Fig. 20. Unwelded blowholes during deformation of metal. X2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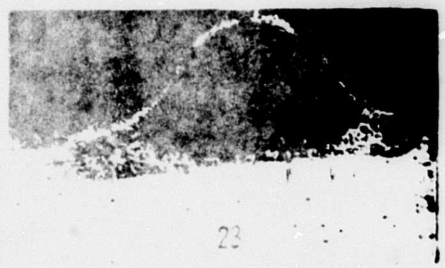
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Fig. 21. Formation of fibrous structure from a dendritic with increase of deformation. ×3 [29]: 1 – deformation 0%; 2 – 65%; 3 – 88%; 4 – 95%.

Fig. 22. Dendritic liquation in bronze. ×100 [21]

Fig. 23. Subsurface bubble, inflating during heating of rolled sheet. ×5

Fig. 24. Liquational heterogeneity of steel ingot. ×0.1 [21]

Fig. 25. Cracks formed along liquational bands in steel **ShKh15**. ×100 [92]

Fig. 26. Liquational "spiders" in steel forging. ×0.5 [31]

Fig. 27. Liquational square in steel rod. ×0.5 [21]

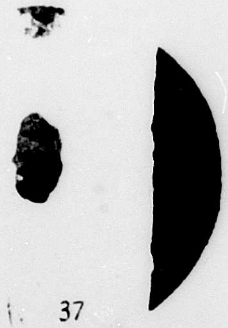
Fig. 28. Break of metal along hot crack in aluminum. ×1 [25]

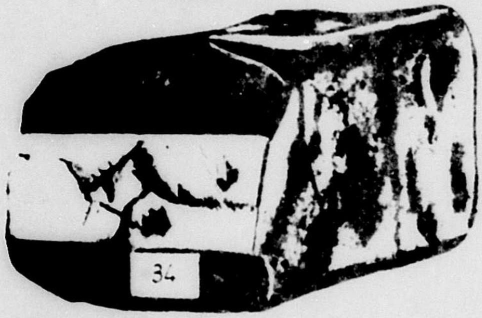
Fig. 29. Stratification along contour of pressed profile from aluminum alloy. X0.5

Fig. 30. Hot crack flooded with eutectic. X100 [46]

Fig. 31. Hot cracks in central zone of ingot. X1 [24]

Fig. 32. Stratification in stamped blank of a turbine disk.





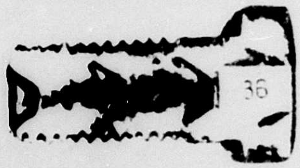


Fig. 33. Forging cracks in high-alloy steel EI402 [31].

Fig. 34. Cracking of axial zone of steel forging. X0.5 [27]

Fig. 35. Line structure in aluminum alloy. X50 [25]

Fig. 36. Internal breaks in bolt from cold-drawn steels [27]

Fig. 37. Hairline crack in a steel rood (cross section). X65 [60]

Fig. 38. Oxidized scale in pressed brass rod. X10 [25]

Fig. 39. "Birdhouses" in rolled steel billets [32]

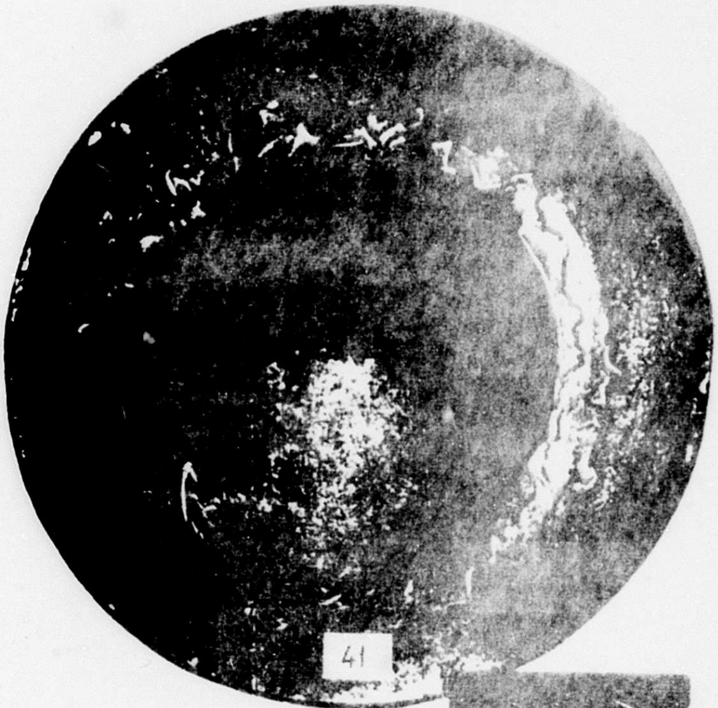
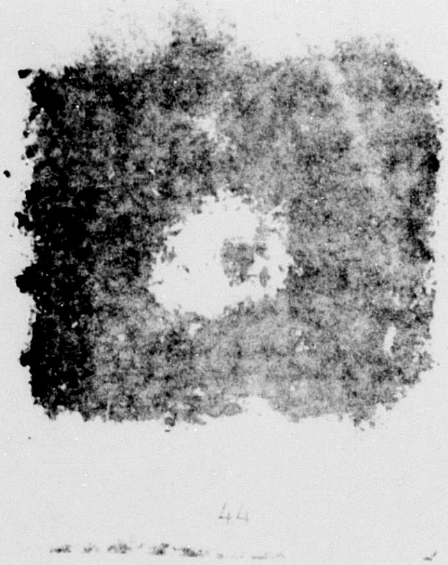


Fig. 40. Coarse-grained structure in steel. ×1.

Fig. 41. Extruded shrinkage cavity in a rod from aluminum alloy. ×1

Fig. 42. Decline on steel billet (shown by arrow). ×2

Fig. 43. Flocs in steel. ×2



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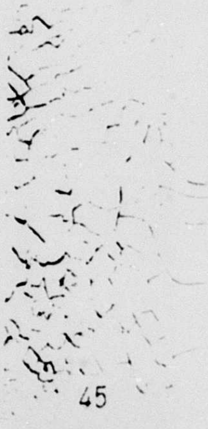

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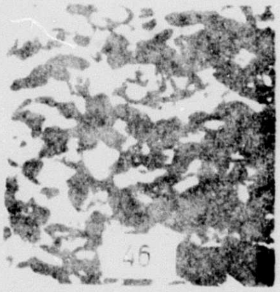

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Fig. 44. Thermal cracks formed during fast heating in a billet. X1 [32]

Fig. 45. Network of surface tempering cracks. X1 [35]

Fig. 46. Intergranular fracture in steel. X5

Fig. 47. Structure of overburning in steel. X300

Fig. 48. Fissure (shown by arrow) on surface of steel billet [32]

Fig. 49. Grinding cracks on surface of hardened steel part. Etched by nitric acid. X0.5 [60]

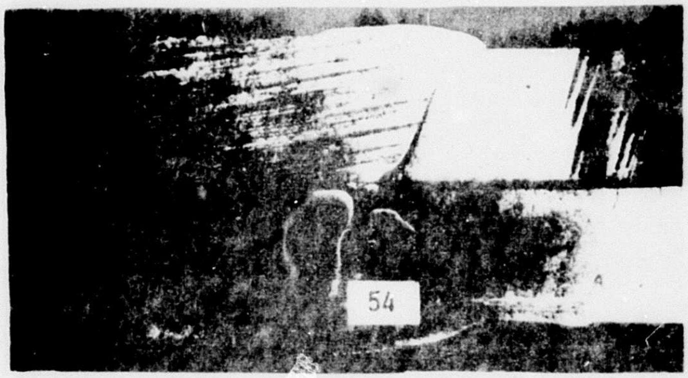

Fig. 50. Burns on surface of steel part [3].

Fig. 51. "Hydrogen" crack on thread of cadmium-plated connecting bar. X300 [19]

Fig. 52. Nonfusion along edge of welded seam. X2

Fig. 53. Cracks in steel pipe, formed under the action of melted solder [19]

Fig. 54. Crack formed in burn zone. [37]


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60
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Fig. 55. Crack in welded seam. ×1.

Fig. 56. Nonfusion in welded point. Steel KhN78T. ×10.

Fig. 57. Crack in steel, formed as a result of corrosion under stress. ×1000 [19]

Fig. 58. Fatigue crack, originating in a deep hammer mark [43].

Fig. 59. Destruction of valve spring due to corrosion [3].

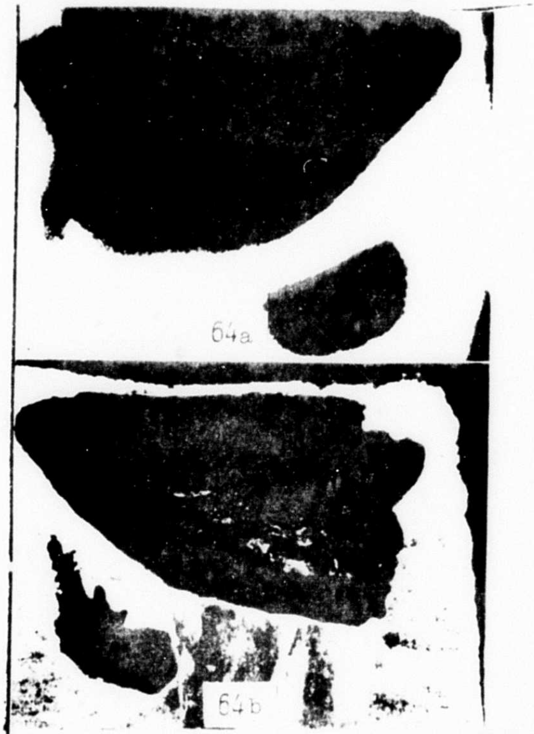
Fig. 60. Fatigue crack starting from floc (shown by arrow) [43].

Fig. 61. Cracks in rivet seam of boiler drum [21].

Fig. 62. Large porosity and shrinkage porosity in aluminum casting (X-ray photograph). x1 [25]

GRAPHIC NOT REPRODUCIBLE

Fig. 63. Slag occlusions in aluminum casting (X-ray photograph). x1 [25]



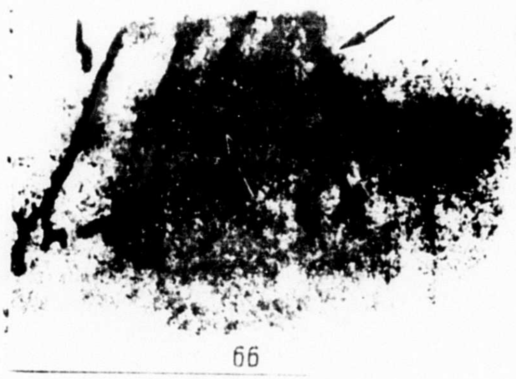
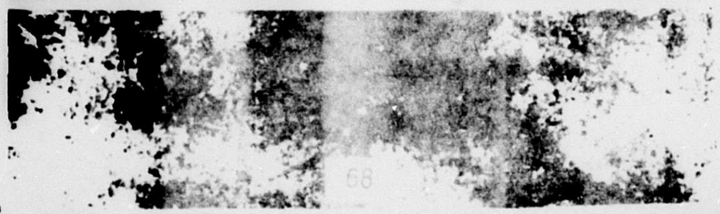
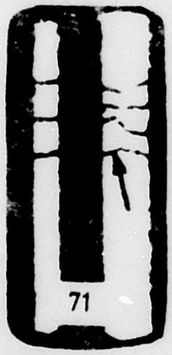


Fig. 64. Shrinkage cavity in large steel ingot: a – gammagraph; b – photograph of cut [55].

Fig. 65. Gas bubbles in steel casting, gammagraph [55].

Fig. 66. Zone damaged by porosity in casting from aluminum alloy: gammagraph [54].





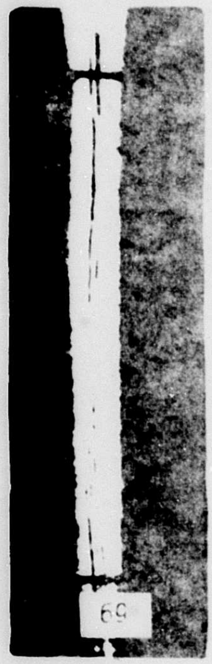


Fig. 67. Longitudinal crack, nonfusion and occlusions in an end-welded seam. Thickness of sheet 10 mm; gammagraph [54]

Fig. 68. Transverse crack in an end-welded seam. Thickness of sheet 5 mm. Gammagraph [54]

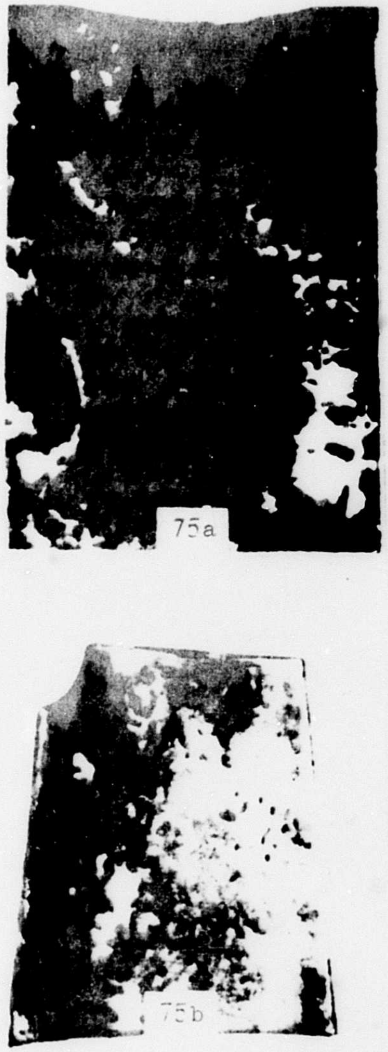
Fig. 69. Hairline cracks on surface of crankshaft revealed by magnetic method [60].

Fig. 70. Tempering cracks revealed by magnetic method [60].

Fig. 71. Grinding cracks on steel roller revealed by magnetic method.

Fig. 72. Fatigue cracks on shaft of reductor revealed by magnetic method [60].

Fig. 73. Flocs revealed by magnetic method [60].



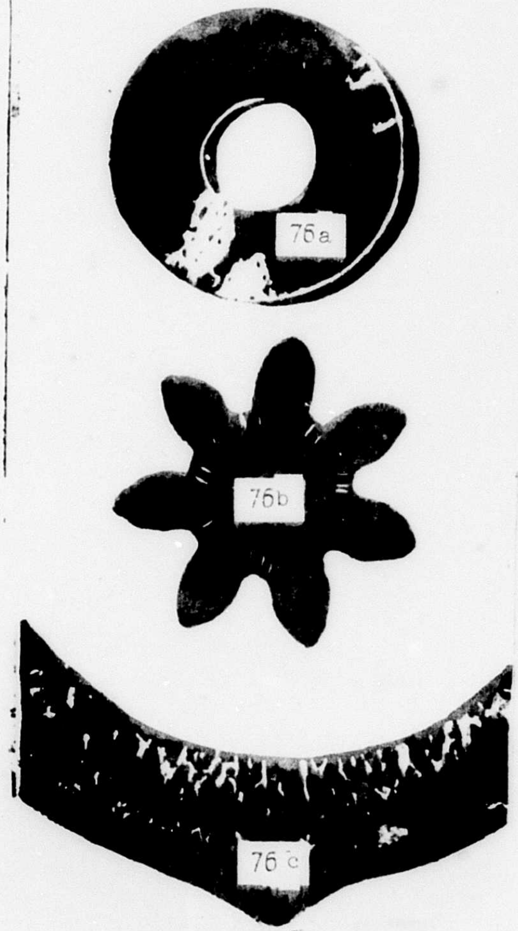


Fig. 74. Cracks - a and shallow porosity - b revealed in welded seams by nonferrous method [74]

Fig. 75. Porosities - a and oxidized scales - b revealed in cast articles by luminescent method [75]

Fig. 76. Grinding - a and b and fatigue - c revealed by magnetic luminescent method [75]

Nonconformity to assigned chemical composition — direct consequence of error allowed during calculation of charge, result of incorrect melt or burning out of separate components of alloy.

Deviation from assigned chemical composition leads to change of operating characteristics of alloy. This form of defect does not permit using casting for important articles.

Nonmetallic, slag and flux occlusions usually enter the casting from the furnace lining and also due to disturbance of technology of melt — ill-timed or incomplete removal of slag, insufficient coating of surface of metal by fluxes, of inaccurate flux discharge during pouring, etc. These occlusions usually have an irregular shape and are in different places of the casting. In hot working by pressure, they as a rule are deformed and destroyed: fragments of them are oriented in the direction of fiber, remaining however, physically separated from surfaces of metal divided by them and prevent welding (Figs. 14 and 15).

Oxides, scales, crusts, fragments of electrodes enter the casting also during melt and casting. They can have volume or surface character, and in deformation, in spite of tight contact with surrounding grains of basic metal, preserve a physical isolation, being disposed in the form of a very thin and hard layer (Fig. 16).

Nonblended regions are formed as a result of interruption of stream of metal during casting or (during continuous casting) due to characteristic peculiarities of advance of metal in crystallizer, and also constitute thin layer of oxides between grains of basic metal (Fig. 17).

Shrinkage cavities and porosities are formed in crystallization, inasmuch as the majority of metals reduces in volume. If special measures are not taken (crystallization directed from the bottom upwards, additional filling by hot metal) upper layers of metal of ingot harden before its core and after termination of crystallization of the ingot in the upper part can be formed large cavities of irregular shape — concentrated shrinkage cavities (Fig. 18). At specific temperature conditions the shrinkage cavity spreads along axis of ingot, piercing it almost over its whole height. In certain alloys under certain conditions of crystallization, instead of a concentrated shrinkage cavity there appears interdendritic shrinkage porosity, damaging a considerable volume of the ingot

(Fig. 19). Internal surfaces of the shrinkage cavity and zones of porosity in considerable degree are usually oxidized and are contaminated, which hampers or excludes the possibility of welding these surfaces in the process of pressure treatment, since it is impossible to ensure sufficiently tight contact between these surfaces and to create conditions for inter-diffusion.

Besides, welding is possibly only under a sufficiently high degree of plastic deformation, conducted at a temperature higher than temperature of recrystallization of metal and ensuring creation of unequal volume conditions defects forming during crystallization of low-alloy steel are welded; defects in high-alloy steels — austentitic, rust-resistant, containing chromium, aluminum, titanium, as a rule are not welded and only are extruded in the direction of the fiber.

Gas porosity appears during crystallization of metal as a result of emission of gases dissolved in it in the melt process. If conditions for the escape of gas bubbles from the ingot are not created, gas porosity can be formed, scattered all over the volume of the ingot or concentrated in the under layer. Formation of gas porosity can be partially prevented by increasing the cooling rate of the casting and practically completely excluded by application of crystallization under pressure, as was shown by A. A. Bochvar and A. G. Spasskiy [28] on aluminum alloys. Blowholes occurring in an ingot during pressure treatment usually are not welded (Fig. 20), especially in high-alloys due to presence in bubbles of a considerable amount of gas and also due to presence in bubbles of a considerable amount of gas and also due to contamination of their internal surface. Moreover, bubbles in deformed metal located near its surface (for instance, in a thin sheet), in the process of heating during hermetic treatment can be inflated due to expansion of gas in them (Fig. 23).

Liquation constitutes heterogeneity of chemical composition of alloy in different points of the ingot and is a serious defect of the ingot. In complex alloys three forms of liquation are observed.

1. Dendritic liquation [29] — heterogeneity of intracrystalline structure — consequence of unbalanced conditions of crystallization of alloy. Degree of liquation depends on nature of alloy and conditions of its cooling in the crystallization process (Fig. 22); it can be in considerable measure decreased by

means of lengthy homogenizing annealing of ingot.

Deformation of metal in the process of its treatment, not removing dendritic liquation, leads to splitting, turning, and flattening of grains, and also different impurities and occlusions. As a result, from dendritic structure is formed a "fibrous" structure of metal (Fig. 21), characterized by considerable lowering of mechanical properties in the transverse direction.

2. Liquation according to specific gravity — heterogeneity of chemical composition along vertical sections of ingot — result of insufficiently thorough mixing of melt and low rate of cooling during crystallization.

3. Zonal liquation — heterogentity of chemical composition along horizontal sections of ingot — two basic varieties: straight, characterized by predominant accumulation in central zone of ingot of fusible components, and reverse, at which fusible components accumulate on surface of ingot. In steel ingots more complicated distributions of liquational heterogeneties are met — liquational cones, "spiders", "mustaches", etc. (Fig. 24). Zonal liquation cannot be removed by homogenizing annealing and during pressure treatment liquational components are oriented in the metal in accordance with direction of its deformation (Fig. 26, 27).

Liquation does not disturb continuity of metal. However, inasmuch as physicomechanical properties of liquational components can sharply differ from properties of basis of alloy (in particular, they can possess embrittlement), strength characteristics of metal in zone of liquational heterogeneity drop, and in this zone frequently destruction starts (Fig. 25). Therefore liquational precipitations on the surface are usually removed by machining or milling before further treatment of ingots.

Hot cracks appear in the process of hardening complex alloys crystallized in a considerable interval of temperatures. The nondurable skeleton of primary crystals, due to appearance of shrinkage stresses, can be destroyed, forming "hot" cracks having strongly oxidized surface and passing along boundaries of grains (Fig. 28). These cracks appear usually in zones of ingot hardening in the last turn, and are formed at temperatures at which elastic properties of metal are low. Sharp cooling prevents formation of hot cracks. However, even in this case, cracks can appear in central zone of ingot, i.e., where cooling occurs slower

(Fig. 31).

In alloys containing a considerable quantity of fusible components (eutetics), the latter frequently fill the cracks which form (Fig. 30), preventing their further development and liquidating distrubances of continuity of metal which appear.

Fins are formed on the surface of the ingot during its hardening as a result of breakthrough of liquid metal from interior zones through its external, still fragile, crust. Fins just as spatters thickened on the oxidized surface, during further deformation of ingots lead to formation of surface scales.

Cold cracks are formed in an ingot after termination of its hardening process. This is connected with the circumstance that with further cooling of the ingot there appear internal stresses of different magnitude and sign it, the result of interaction of surface and depth layers of metal, tending toward expansion or contraction. During cooling of ingot there is always a temperature drop along the section which is bigger the greater the relationship of volume of ingot to its surface aht the less the temperature transfer of material of ingot. Upon sharp cooling of an ingot from copper [30] — material with very high temperature transfer — this drop can attain 200°C, and in an analogous ingot from carbon steel, whose temperature transfer is an order lower than for copper, 800°C. With such a drop of temperatures the core of the ingot tends to expand and the surface layer — to compress. As a result of this temperature internal stresses appear (compression in core of ingot and extension in its surface layers). Besides, a temperature drop can lead to nonuniform flow of phase transitions (along cross section of ingot). Moreover in different layers according to depth different structural components are formed which can differ in specific volume. This in turn causes the appearance of internal structural stresses. Internal stresses can appear also due to a difference of coefficients of linear expansion of different structural components of alloys independently of drop of temperatures and phase transitions.

There are fully possible cases when internal stresses appear as a result of simultaneous action of several of the considered causes.

Internal stresses with sufficient magnitude and limited ability of metal to elastic and plastic deformation, are also a cause of appearance of various kinds

of cold cracks, differing from hot by the absence of strong oxidation of surfaces.

Probability of formation of such cracks is high for high-alloy steels and alloys possessing low temperature transfer, smaller plasticity, and containing structural components with different specific volume and coefficients of linear expansion.

In the process of pressure treatment metal is deformed by means of intracrystalline shifts and twinning, and also by means of a shift of some grains relatively to others. Moreover depending upon the setup of the strain state in metal there appear internal stresses of different signs. Stretching internal stresses at a specific orientation can lead to appearance of breaks and cracks of metal, first of all in zones weakened by presence of the above defects of the ingot. With sufficient magnitude of tensile stresses breaks and cracks can be also formed and in metal not injured by defects (compression stresses, especially at unequal volume compression, conversely, prevent formation of internal breaks and cracks in solid metal and promote welding of internal defects in the ingot). To what was said it is necessary to add that during pressure treatment metal is repeatedly subjected to heating and cooling, which also leads to appearance of thermal stresses promoting formation of internal breaks and cracks. Besides, in complex alloys and high-alloy steels breaks and cracks can appear under the action of structural stresses connected with presence in alloy of structural components whole resistance of deformation differs from resistance of basis of alloy.

All this leads to the circumstance that during pressure treatment [31, 32, 33] defects of ingot turn into various kinds of cracks, stratifications, hairline cracks (thin strokes fractions of mm to several cm long, located on surface of metal and in the subsurface layer, and the result of deformation of nonmetallic occlusions and blowholes) internal and surface scales, and crusts (rolled or expanded fins or splashes — thin tongues of metal tightly fitting against it but easily peeled), volume discontinuities "birdhouses", internal transverse ruptures, etc., lead to formation of "stitched" structure, liquational square, forging cross. Besides, in sound metal defects characteristic for the very processes of deformation can appear, such as forging, stamping, rolling, pressing, drawing — internal cracks, breaks extrusion shrinkage cavaties, stratification of longitudinal seam, flows, impediments, settings and also variable wall thicknesses, fullerings,

and thickenings of walls, dents, notches, and others (Figs. 32-42).

So that surface defects do not enter ready articles, they are removed from the surface of ingots and deformed billets by milling, planning, machining, cutting, stripping, or burning out by an oxyacetylene flame (fire stripping).

During fire stripping considerable thermal stresses appear which can lead in turn to formation of surface cracks developed in the process of further treatment of a billet.

Very wide-spread defects of steel — flocs — are thin winding cracks, appearing as a break of a spot with silvery surface character, round with a diameter up to 50 mm (Fig. 43). Flocs are most frequently formed in medium-carbon and medium-alloy steels (chromium steels, chromium-nickel steels and chromium-nickel-molybdenum steels) when there is an increased amount of hydrogen in them.

Hydrogen dissolved in molten steel in the cooling process and especially during phase transitions, due to sharp lowering of solubility, tends to be liberated. It fills all space up to defects of crystal lattice, and, being transformed from atomic into molecular, develops huge pressures leading to brittle rupture of metal.

Flocs usually appear in the central zone of forged or rolled billets of large cross sections and more rarely — in ingots. Liquational heterogenity, presence of structural and thermal stresses assist the formation of flocs, which are disposed along the liquational square or along the forging cross. At sufficiently great deformation of billets, flocs having an unoxidized surface can be welded but can also open, forming "birdhouses". The danger of flocs is that they can form in a billet cooled after hot working during a very prolonged "incubative" period (up to two months) at room temperature.

In stainless steels of austenitic, ferrite, and martensite classes, and also in high-speed cutting steels, flocs as a rule are not encountered [34].

A considerable quantity of very dangerous defects can form during heat treatment of parts. Basic causes of formation of defects are nonobservance (mainly exceeding) of assigned temperature, time of holding, and also rate of heating or cooling the part.

A consequence of exceeding the assigned temperature is overheating or overburning of metal. Overheating leads to formation of coarse-grained structure

characterized for a number of steels by naphthalene and intergranular fracture. Overburning causes "spoilage" of boundaries of grains of metal and sometimes even their fusion, which promotes further destruction of metal.

Overheating and overburning can be manifested even without exceeding the assigned temperature of treatment in zones enriched by fusible componets. Local fusion can be observed and even destruction of metal (Figs. 40, 46, and 47).

Excessively fast heating, especially during treatment of large articles, can lead to appearance of considerable tensile stresses in the core of the part and to appearance of thermal cracks (Fig. 44). During sharp heating or cooling (for instance, during hardening), just as occurs during fast cooling of a crystallized ingot, thermal stresses appear from temperature drop over the cross section and also structural stresses connected with the circumstance that structural transformations along the cross section of the part do not occur simultaneously.

Besides, due to decarburizing or carburizing of surface layers during heat treatment of steel, disturbance of correct composition of atmosphere of furnace, and also as a result of sharp change of chemical composition of surface layer, during chemical-heat treatment in surface layers of a part a structure sharply differing from the basic can form. This leads to appearance of internal structural stresses [35]. As a result ot the imposition of thermal stresses on structural stresses, in the hardened part tempering cracks of different magnitude and orientation can appear. Their character is conditioned by distribution and relationship of the mentioned stresses and also properties of the alloy. They can start on the surface of the part and spread deep into it, oriented basically along the axis of the part, or can be internal, appearing in the core of the part and oriented in the transverse direction; also possible is the formation of surface cracks spreading in the form of a fine network at a depth of several hundredth fractions of a millimeter, and continuing in the form of separate cracks to a depth up to 2 mm (Fig. 45).

During the grinding of hardened steel articles, due to the sharp heating of the surface layer there occurs a sudden and nonuniform temper of martensite. The surface layer tends to be reduced in volume; in it there appear tensile stresses leading to appearance of characteristic network of grinding cracks (Fig. 49).

It is possible, however, to imagine the opposite case, when in the surface layer there appear compression stresses. Here is possible the appearance of tensile transverse deformations and the formation of sliver cracks. Such cracks are formed only when in a very thin layer of order of several microns there occurs a change of sign of stresses: tensile stresses pass into compression stresses.

Finally, under the action of stresses of the second kind in hardened steels [36] microcracks (for instance, in needles of martensite) can form.

On different stages of the technological process steel parts are subjected to action of solutions of alkalis and acids (degreasing, etching) and also electrical treatment in special solutions. The surface layer of steel can be saturated by hydrogen, which leads to sharp fall of plasticity and to brittle ruptures, the location of which usually becomes microcrack on the surface of the part [19]. The appearance of hydrogen cracks explains many cases of so-called "inadvertent" (in reality delayed) destruction of loaded steel parts (Fig. 51) having galvanic plating and not subjected to a special "dehydrogenating" temper.

In the process of chemical-heat treatment, due to disturbances of technological conditions deviation from assigned thickness of layer can appear. Exactly so, during electrochemical treatment of parts, especially parts of complicated form, distribution of current along surface can be nonuniform. This leads to deviation of thickness of protective (for instance, oxide) coating from the assigned.

Metallic parts and half-finished products subjected to heat treatment frequently turn out to be warped due to presence of residual internal stresses in them. To prevent warping of the parts (more frequently, half-finished products — sheets, rods, profiles, pipes) are subjected to correction (straightening) — bend or extension. On the surface of the part straightening cracks can be formed. During the assembly of parts in a construction (bolt connection, pressing, etc.) also in many cases considerable stresses leading to formation of assembly cracks can appear.

Surface microcracks appear also during "cold" machining of forced conditions not corresponding to the properties of the processed material.

It is necessary to note that under forced conditions of grinding on the surface of a part [37] dangerous defects can appear — burns (Fig. 50). These are

cross sections of sharply hardened metal, being the sources of brittle rupture with formation of cracks (Fig. 54).

A thin fragile layer can be formed also as a result of autogenous cutting of steel parts [38].

Surface contact cracks frequently are formed on loaded metallic parts in the place of contact with fused metals, moistening the surface of these parts. Liquid stannous solders, babbit, and bronze penetrate the microcracks on the surface of a part, exposed under the action of applied stresses; cracks are developed and destroy the part. Such contact can take place during technological operations, for instance, during soldering (Fig. 53), and in exploitation, for instance, during the melting of the antifriction layer in an overloaded dry bearing. The mechanism of development of cracks formed under the influence of fused metals (as also the mechanism of development of "hydrogen" cracks) is explained according to P. A. Rebinder by the influence of superficailly active liquid media adsorbed by the surface of the metal and creating a cleaving effect upon penetration into the microcracks.

Processes of manufacture parts intended for use in complex units frequently provide a rigid connection of elements of the construction of these parts by means of welding, soldering, riveting, diffusion cohesion, and gluing. These technological operations also can lead to the appearance of different, frequently very dangerous, defects.

Thus, during arc and gas welding metallurgical defects can appear in fused metal which is subjected to melting and hardening, and consequently can have all the defects inherent to cast metal. Besides, under the influence of high temperature transformations in the zone adjacent to the seam (zone of thermal influence) of the basic metal can occur, as a result of which changes of dimensions of grain, overheating, hardening and tempering can appear. If separate layers of the built-up metal are not connected or the built-up metal is not connected with the base metal, a very dangerous defect occurs — nonfusion (Fig. 52). Finally, in the cooling process of a welded joint under the action of thermal and structural stresses which appear in the seam and in the zone of thermal influence, hot and cold cracks can be formed (Fig. 55). Probability of formation of cracks during welding is increased with complication of composition of alloys from which the welded parts are prepared and with increase of thickness of welded parts [39, 40].

Under different forms of resistance welding – butt, spot, and seam, analogous defects, mainly cracks and nonfusion (Fig. 56), can be found.

The basic defect of a soldered connection [41] is the presence of unsoldered zones and flux contaminations, as a rule the consequence of insufficient purity of preparation of soldered surfaces or disturbance of the temperature regime of soldering.

These causes, and also nonobservance of assigned conditions with respect to temperature and pressure, leads to appearance of zones of disturbance of cohesion between elements of multilayer articles (brake disks, clutch disks, bimetalic sheets and wire plated sheets, rods and pipe, etc.).

An analogous defect – zone of ungluing – can be observed [42] in different recently widely applied aviation and rocket constructions, parts prepared by means of bonding metallic materials to each other or metallic materials with nonmetallic.

Defects can appear not only in the manufacture of parts, but also in their exploitation. Destruction is not an instantaneous act, but occurs gradually as a result of development of cracks appearing in the "hearth" zone. As a result of blending over the volume of an article, the initial stage of their development presents therefore great interest, since in many cases it is possible prevent a breakdown. As a rule in the zone of excessive concentration of stresses caused either by impractical construction of a part or by metallurgical or other defects cracks appear. They can start on the surface of the part or deep inside it; they can appear as the result of application of brief long single repeated static or dynamic loads, and also multiple sign-alternating mechanical and thermal fatigue loads (Fig. 60). In the last case a special role in reducing the strength of a part is played [43] by various kinds stress concentrators, which sometimes can be even "accidental", for instance a nick from a deep hammer mark (Fig. 58).

During storage and transportation of parts and half-finished articles besides defects due to inaccurate conversion (nicks, scratches, dents, wear) or due to influences of humid atmosphere (corrosion), cracks can appear whose cause of appearance is residual stress in the part.

In a number of cases parts in the process of exploitation are subjected to influence of aggressive media leading to corrosional destruction. Corrosional destruction can be [44] surface destruction, leading to damage of the whole surface

or specific sections (see Fig. 59), or intercrystalline, penetrating depth of metal from the surface side subject to the influence of this medium mainly along boundaries of grains. Intercrystalline corrosion especially sharply lowers strength characteristics of metal.

Finally, as a result of corrosion, under stress cracks can be formed (Fig. 57), of encountered in steel, brass, aluminum and magnesium alloys. Such cracks are formed, for instance, in rivet seams of boiler drums ("caustic fragility"), in brass articles ("seasonal cracking"), etc. (Fig. 61).

We considered only the basic defects, most frequently met in metallic parts and half-finished products. This by far not the full survey once again shows that defects are quite various with respect to their origin, nature, dimensions, location, orientation with respect to fiber and with respect to their physico-mechanical characteristics and also their behavior in the process of technological treatment.

All defects, however, are united by general criterion: they cause more or less sharp change of physical characteristics of a medium, such as density, electrical conductivity, permeability elastic properties, etc. Defects distributed in boundary zones — liquational accumulations, zones of incomplete hardening, zones of corrosional damage, local cold hardening, and others, cause less sharp change; defects which are local, localized in a small volume, constituting different disturbances of continuity (cracks, cavities, pores, stratifications, flocs, and others) cause a sharper change.

The investigation of changes of physical characteristics of a medium and detection in such a way of imperfections of its structure — defects which are the cause of these changes — is the physical basis of nondestructive methods of regulation. These methods are based on comparison of physical characteristics of the material of the regulated part in different sections of it. The sections in which disturbances of homogeneity of structure of material are lacking (or are found in permissible limits) play the role of standard. Thus defects which are local and distributed in limited zones can be revealed. Regard, however, defects distributed all over the volume of a part or along its surface, comparison, of course, is possible only with another part accepted as the standard.

Methods of nondestructive regulation, as will be shown below, can reveal different defects in metallic (and nonmetallic) parts, investigating different

physical characteristics of the material of these parts.

In Soviet and foreign practice different physical methods of nondestructive quality control of materials are widely applied, [45-74][1] based on investigation of changes of conditions of the propagation of different kinds of penetrating radiations (electromagnetic and elastic oscillations), investigation of magnetic and electrical properties of material, and also the phenomenon of capilarity.

Development and improvement of physical methods of nondestructive control, development of special equipment, methods of control of an article of specific type, and scientifically proved norms of their rejection composes a complex of measures ensuring realization of one-hundred percent control of the quality of articles from different materials and united by the general concept of "defectoscopy of materials".

3. Basic Methods of Nondestructive Control[2]

Table 1 gives characteristics of the most effective methods of defectoscopy, based on use of electromagnetic phenomena and phenomena of capilarity.

Rational application and correct combination of these methods makes it possible to reveal various defects (Figs. 62-76) encountered in metals. In a number of cases contactless control is possible, allowing investigation, for instance, of quality of a part heated to a considerable temperature.

However, a large group of defects are not detected by any of these methods. First of all this includes defects in cast and deformed billets and parts of large cross sections — ingots, blanks for rotors of powerful turbines, blanks for large stamps, propeller shafts, parts of landing gears of heavy aircraft, etc.

This is explained by the fact that X-rays and gamma rays do not "pierce" such sections; radiation of a betatron can be used only up a thickness of 0.5 m, and even that only in isolated cases due to complexity, cumbersomeness, and small mobility of the apparatus. Magnetic defectoscopy, usually applied for detection of surface defects, in this case also cannot be used since magnetization of parts of large dimension is a complicated problem. Possibilities of detection of surface

[1]See also G. V. Akimov. Author's certificate No. 53417 USSR 1937.

[2]Methods founded on use of elastic oscillations are not considered in this section.

Table 1. Comparative Characteristics of Basic Methods of Nondestructive Control

Method	Physical bases	Basic field of application	Revealed defects, measured quantities, regulated parameters	Sensitivity	Basic characteristics of utilized equipment
1. Visual	Different reflection of light from heterogeneities of surface of regulated article.	Control of external and during use of special attachments — also internal surfaces	Surface cracks, double skins, settings, impediments, porosities, etc.	In regulation by the naked eye — defects in extent of tenths of a millimeter; with use of optics — several hundredths of a millimeter.	Simple and binocular magnifiers, periscopic devices for inspection of internal surfaces
2. Roentgenradioscopy	Different absorption of beams by sound and defective sections of article	Casting and butt-welded joints. Limiting thicknesses for industrial X-ray apparata, mm: steel.....80-100 light alloys...350 copper alloys...50 (with use of betatron: steel — up to 500 mm)	Surface and depth cracks oriented along direction of radial line, cavities, porosities, liquational extrusions, nonmetallic and slag occlusions, etc.	Defects of dimension (in direction of radial line) ≥3% (steel) and ≥10% (light alloys) from thick article. Width ≥0.025 mm. Dimensions of projection of defect are determined directly. Special methods can determine depth of bedding of defect	Complicated cumbersome and expensive high-voltage equipment, requiring special protection from influence of beams and special locations. In separate cases portable equipment can be used
3. Radioscopy by gamma rays	The same	Massive cast articles and butt-welded joints. Articles of complicated configuration. Radioscopy under field conditions	The same	Approximately the same	Simple and compact. Special protection from influence of beams and special locations is required
4. Magnetic powder	Attraction of particles of magnetic powder to places of location of defects, provoking dispersion of magnetic flux in magnetized part.	Parts and half-finished products of any form from ferromagnetic materials (mainly from structural steels)	Cracks, hairline cracks, flocs, and other defects located on surface (up to 2.5-3 mm). Length of defect is determined directly, width of defect is sharply increased. Depth of bedding of defect is estimated roughly	Cracks with cross section from 0.01 × 0.01 mm, hairline cracks with cross section from 0.05 × 0.05 mm	Special magnetizing and demagnetizing devices, working from power-supply network of industrial voltage. Measures of protection general for industrial electro-installations

Table 1. Comparative Characteristics of Basic Methods of Nondestructive Control (cont'd)

Method	Physical bases	Basic field of application	Revealed defects, measured quantities, regulated parameters	Sensitivity	Basic characteristics of utilized equipment
5. Magnetic powder	Registration and quantitative evaluation of flow of dispersion with the help of probes measuring a permanent magnetic field or its gradient	Intermediate products and small mass parts (standard) and also rails in exploitation	The same defects, but at a depth up to 30 mm; measurement of thickness of sheets, walls of vessels during bilateral access, detection of heterogeneity of structure	Approximately the same	More compact (as compared to powder method) allowing automation of control process
6. Magnetographic	Registration and quantitative appraisal of flow of dispersion with the help of magnetic-sensitive tape	Butt-welded seams of thickness up to 16 mm	Cracks, poor penetration, slag occlusions pockets, and other defects of welded joints	Thin cracks and poor penetration of dimension ≥10% (from thickness of welded joint)	Portable with autonoma feeding for work in plant and field conditions
7. Magnetic structuroscopy	Dependence of basic magnetic characteristics of ferromagnetic materials on their structure and properties	Mass parts and intermediate products (rods, pipes) from ferromagnetic materials	Chemical composition, structure, mechanical and physical properties textures, and anisotropy of structure and properties of materials		Simple electrical measuring equipment
8. Magnetic thickness gauge	Dependence of force of interaction between magnet and tested part on thickness of part or coating	Different parts and intermediate products from ferromagnetic materials	Thickness of layers of galvanized, varnished and painted and other coatings, of nonmagnetic layers of bimetalic articles of sheets, of walls of pipes and hollow articles (for one-sided access)	Around 4% (from measured thickness)	Simple compact portable instruments

Table 1. Comparative Characteristics of Basic Methods of Nondestructive Control (cont'd)

Method	Physical bases	Basic field of application	Revealed defects, measured quantities, regulated parameters	Sensitivity	Basic characteristics of utilized equipment
9. Electrical resistance	Different resistance of sound and defective sections and also sections with different cross section	Different articles of simple form	Thickness of sheets, walls, pipes and hollow articles for one-sided access, depth of cracks leading to surface, presence of stratifications	Depends on homogeneity of properties of material of article, cleanness of treatment of surface, and several other factors	Electrical measuring equipment supplied by complicated multiple-contact measuring head
10. Electroinductive (method of eddy currents)	Electromagnetic interaction between coil fed by alternating current and an article in the field of this coil	Different parts and intermediate products from ferromagnetic and nonferromagnetic metals	Disturbance of continuity oriented in a plane not parallel to surface. Chemical composition, structural state. Thickness of sheets and layer of coatings, diameter of wire, of rods, electrical conductivity (contactless measurements)	Cracks of depth ≥0.25 mm	Compact radiomeasuring equipment especially convenient for control of articles in continuous production and easy automated
11. Thermoelectric	Appearance of thermoelectromotive force upon heating the contact of heterogeneous metals	Intermediate products and parts from ferromagnetic and nonferromagnetic metals	Chemical composition of material (sorting by brands), thickness of coverings		Compact, not complicated in conversion
12. Triboelectrical	Appearance of electromotive force under friction of heterogeneous metals	The same	Chemical composition of material (sorting by brands)		The same
13. Electrostatic powder	Attraction of positively charged particles of powder to places of location of cracks on surface of regulated part	Enameled or glazed metallic parts and also parts from plastics	Surface cracks	Crack with opening over 1 μm	Limitedly simple and safe

Table 1. Comparative Characteristics of Basic Methods of Nondestructive Control (cont'd)

Method	Physical bases	Basic field of application	Revealed defects, measured quantities, regulated parameters	Sensitivity	Basic characteristics of utilized equipment
14. Nonferrous capillary	Manifestation of defective sections (filled preliminarily by liquid dye) against the background of a coating specially applied to the part	Parts (mainly cast) from metals and also from plastics	Surface cracks, porosities, oxidized double skins, impurities of zone damaged by intercrystallite corrosion, etc.	Cracks with opening >0.01 mm and depth >0.03 to 0.05 mm. Extent is determined directly, width of cracks is sharply distorted (is increased)	Limitedly simple equipment (reagents are very toxic and inflammable)
15. Luminescent capillary	Filling of cavity of defect by luminescent liquid during irradiation by ultraviolet light	The same	The same	The same	Somewhat more complicated equipment but does not require application of such toxic reagents.
16. Magnetic luminescent	The same as in magnetic powder method, but particles of magnetic luminescent powder gleam at illumination by ultraviolet rays	The same as in magnetic powder method, but regulation of articles with dark surface is possible	The same as in magnetic powder method	Cracks of width >0.0002-0.0005 mm, and depth >0.01 mm	Equipment of magnetic powder and luminescent methods is combined

defects by capillary methods and the method of eddy currents are very limited.

In parts of "average" cross sections, pierced by X-rays and gamma rays (stamped blanks for disks of gas turbines and compressors, rolled plates, pressed profiles, and rods) these methods cannot reveal internal stratification and thin cracks, zones of crystallization, and also volume heterogeneities for a small difference of densities of material of heterogeneity and alloy base.

In parts of any corss sections, even the thinnest — rolled sheets, bimetalic articles (brake disks, clutch disks, bearing linings), multilayer articles with thin sheet sheathing and metallic or nonmetallic sheathing (foam plastic) or, finally, a honeycomb filler — as a rule, with the exception of separate cases of possible application of the method of eddy currents stratification, disturbance of cohesion, nonsoldered places, nonglued places, and also many surface defects cannot be revealed.

Obviously, for detection of defects not revealed by the enumerated methods, only methods based on the use of penetrating radiation possessing properties sharply differing from properties of X-rays and gamma rays can be applied. So that control of parts of large cross sections is possible, this radiation should possess great penetrating ability. So that it is possible to reveal thin stratifications, nonsoldered places, nonglued places, energy of radiation should in strong degree be reflected from boundary of basic metal and defects included in it. Coarse-grained zones can be revealed if this energy is dispersed in different degree by big and small grains.

Such radiation, possessing great penetrating ability (it is possible to "pierce" the part whose cross section is measured by meters), reflected from the boundary of two media with sharply different physical properties, dispersed by big crystals sharply attenuating in zones damaged by intercrystallite corrosion is ultrasonic oscillations.

Application of ultrasonic oscillations for nondestructive quality control of materials (ultrasonic defectoscopy) was proposed in the USSR in 1928 by S. Ya. Sokolov.[1] However over approximately a decade, ultrasonic defectoscopy did not have wide application and was developed comparatively slowly. At the

[1]S. Ya. Sokolov. Author's certificate No. 23246, USSR, 1928.

end of thirties, mainly in aviation industry in connection with beginning of production of heavy aircraft and powerful engines, appeared new problems which were impossible to solve by existing methods. This in considerable degree stimulated development of methods of ultrasonic defectoscopy.

At present ultrasonic defectoscopy, recognized in the USSR and abroad, is one of the most universal methods of nondestructive control and continues to be developed in different directions, allowing the solution of ever more complicated problems of nondestructive control, and the determination of certain physico-mechanical characteristics of material in conditions hampering use of other methods.

In this work, written on the basis of extensive literaturary material published by Soviet and foreign researchers with use of rich experience of workers of industry and also results of investigations carried out by the author with colleagues in a period of over 25 years physical bases, technical characteristics, methodology, regions of rational application, and development of methods of ultrasonic defectoscopy are considered.

II

PHYSICAL BASES OF ULTRASONIC DEFECTOSCOPY

1. Nature of Ultrasonic Oscillations

Ultrasonic defectoscopy uses elastic vibrations and waves propagating in media possessing elastic properties [77-94]. Particles of medium do not shift in the direction of propagation of the wave, but oscillate near their own positions of equilibrium. Wave motion is the propagating oscillatory process at which in the direction of its propagation is transmitted energy of vibrations. Let us agree to call the locus of points which at an assigned moment of time the oscillatory process reached the wave front and the direction in which this process propagates — a beam.

It is possible to observe and to study wave motion with the help of a plane model with linear wave front (for instance, surface of water on which waves spread). However using this model, giving very graphic representation about processes occurring during propagation of waves, one should not forget that waves on the surface of water are not elastic but gravitational, since particles of water, deviating from position of equilibrium, return to this position not by forces of elasticity but of gravity.

In an unbounded uniform isotropic medium propagation of elastic waves has a spatial character. Moreover depending upon form of front, waves can be flat, spherical, and cylindrical.

Depending upon elastic properties of a medium, in it can propagate elastic waves of different types, differing by direction of displacement of vibrating particles. If oscillations of particles occur in a direction coinciding with

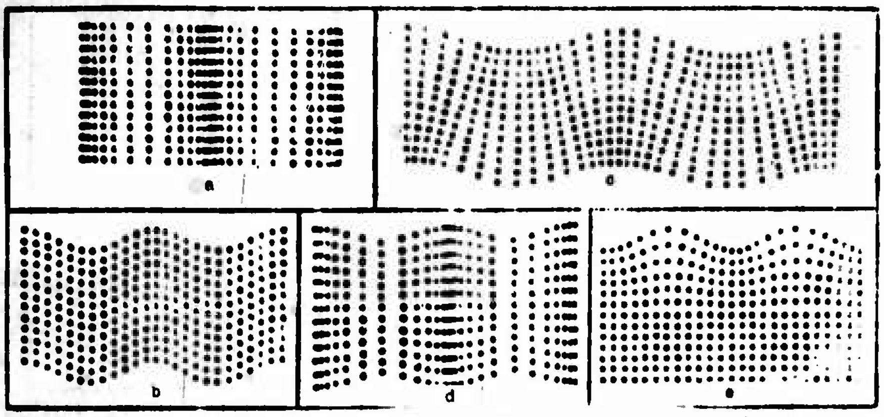


Fig. 77. Elastic waves propagating in a solid isotropic medium: a – longitudinal; b – shear; c – bending d – expansion; e – surface.

direction of propagation of wave (with direction of beam), such waves are called longitudinal. Longitudinal waves can propagate in solid liquid, and gaseous media. Due to the circumstance that particles of a medium during propagation in it of longitudinal elastic waves oscillate in the direction of the beam the structure of a longitudinal wave constitutes an alternating of zones of compressions and rarefactions (Fig. 77a). Longitudinal elastic oscillations with a frequency within the limits of ~16 Hz-20 kHz are picked up the human hearing apparatus in the form of sound. Longitudinal oscillations of lower and higher frequencies are not audible to a human and are called correspondingly infrasonic and ultrasonic.[1]

If the direction of vibrations of particles of a medium is perpendicular to direction of propagation of wave, waves are called transverse shear (Fig. 77b). Shear waves can propagate in a solid medium. Gases and liquids do not possess elasticity of form (shear elasticity), and therefore propagation of shear vibrations caused by the provoking shift elastic deformation, in gases and in the absolute majority of liquids, is impossible. Only in polyisobutylene and certain high-molecular liquids, thanks to presence of elasticity of form, is propagation of shear vibrations by a small distance possible.

Longitudinal and transverse elastic waves (basic types of elastic waves) can propagate in pure form only in an unbounded medium or in extreme measure, in a body whose dimensions in directions not coinciding with direction of propagation of wave considerably exceed length of the latter.

[1]Subsequently ultrasonic oscillations will be abbreviated UZK.

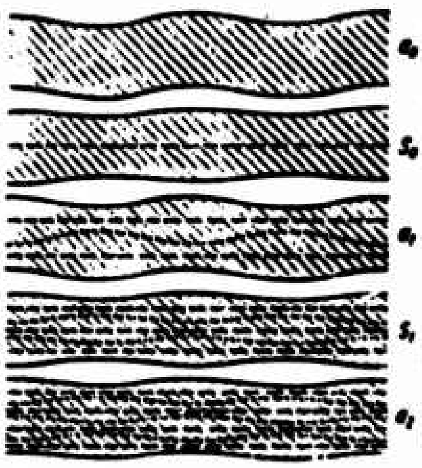


Fig. 78. Normal waves propagating in a thin plate: a_0, a_1, a_2 — bending waves of zero, first, and second orders; S_0 and S_1 — expansion waves of zero and first orders.

If dimensions of body are comparable with with length of elastic wave, the appearance of bending waves (Fig. 77c) is possible, differing from shear waves in that planes of cross section do not remain oriented perpendicularly to direction of beam as occurs during propagation of shear oscillations, and deviate a certain angle to both sides. Purely bending waves are obtained in plates whose thickness is small as compared to wavelength.

Upon excitation of longitudinal vibrations in a body bounded in two directions, for instance in a rod, due to transverse compression of the extended zone, expansion waves can propagate (Fig. 77d), characterized by displacement of particles along a beam and perpendicular to it.

On the free surface of a solid body surface waves or Rayleigh waves can propagate. Particles accomplish motion along ellipses oriented in the plane formed by a ray and the normal to the surface of the body. Amplitude of vibrations of particles with removal from free surface decreases exponentialy, and therefore the wave propagates in the body only to a depth of the order of a wavelength.

During [UZK] (УЗК) propagation in thin sheet, for instance in a thin-walled shell (pipe, cylinder), or wire there can appear normal or free waves, in foreign literature frequently called "waves in a plate" (Plattenwellen, Plate Waves), "wire waves," or Lamb waves.

Normal waves are excited usually as a result of transformation of longitudinal UZK, incident on the surface of a sheet or pipe under certain angles different from zero. A normal wave of given type (symmetric — expansion wave or antisymmetric — bending wave) and order (Fig. 78) is excited at defined discrete values of the angle when its phase speed coincides with phase speed of incident longitudinal wave.

In long rods and pipes can spread also torsional and longitudinal radial waves can also propagate.

In ultrasonic defectoscopy at present longitudinal and shear waves of flat

and spherical form and also surface, bending normal waves are widely used.

Such variety of types of waves utilized in ultrasonic defectoscopy, considerably larger than in other regions of ultrasonic technology, lead to necessity of expansion of the concept of ultrasonic vibrations and waves.

Above the conventional definition of ultrasonic vibrations was given as vibrations whose frequency exceeds a certain limit (20 kHz), caused by physiological peculiarities of the human hearing apparatus. However, first, this limit is very conditional, inasmuch as it depends on individual properties of hearing organs for different people and on the level of loudness, and secondly, and this is basic, shear surface, bending and other type of waves utilized in ultrasonic defectoscopy, inasmuch as they cannot propagate in air are not perceived by the hearing apparatus, are directly inaudible at any frequency, and therefore cannot be called sound. It is impossible, consequently, to call shear vibrations of a frequency, for instance, of 30 kHz, ultrasonic on the basis that this frequency lies higher than the limit of audibility. Obviously it is more correct in such a case to talk not about ultrasonic but about high frequency elastic vibrations.

Exactly so, it would be more correct to say "defectoscopy with the help of high frequency elastic vibrations." Preservation of the term "ultrasonic defectoscopy" is a tribute of tradition and the desire to use a shorter term.

Subsequently by the term "ultrasonic vibrations" will be therefore understood elastic vibrations of all types, frequency of which exceeds a certain purely conditional limit equal to 20 kHz.

Now by different methods ultrasonic vibrations of frequency from 20 kHz to $\sim 10^9$ Hz can be obtained. Moreover in solid media wave length can attain a magnitude comparable with wave length of visible light (near 1 μm). Elastic vibrations of still higher frequencies – higher than 10^9 Hz are frequently called hypersonic. Length of elastic waves of hypersonic range approaches the magnitude of interatomic distances, and at frequencies of the order 10^{12} Hz elastic oscillations obtain the character of thermal motion. Therefore along with phenomena described by laws of acoustics of audible range, with increase of frequency of elastic vibrations their properties connected with smallness of wavelength and described by laws of geometric acoustics appear to an ever larger degree.

High frequency elastic vibrations possess a number of specific properties

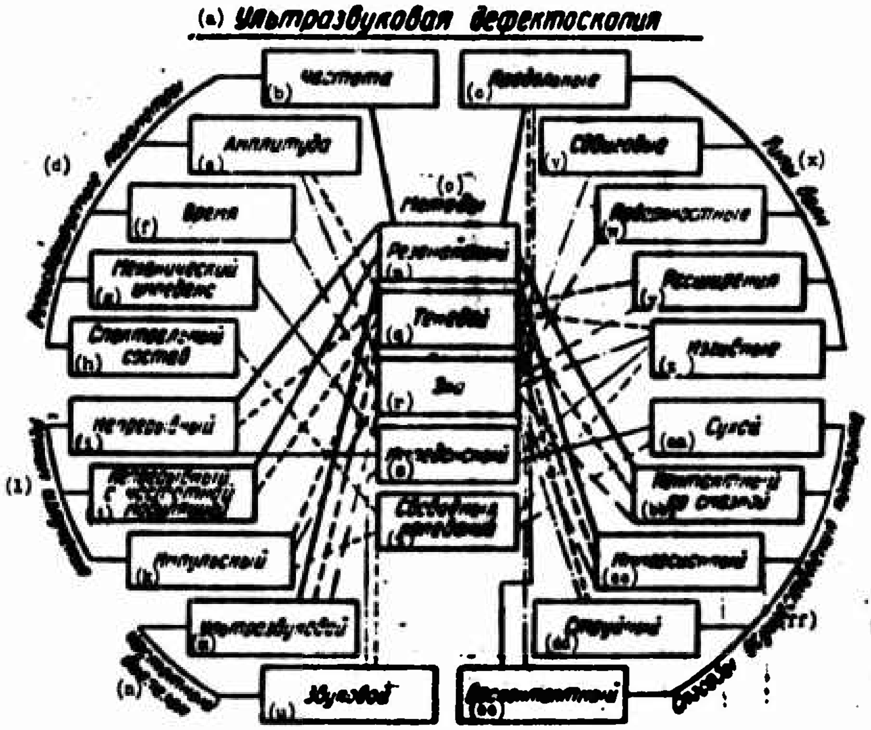


Fig. 79. Methods of nondestructive control with the help of elastic vibrations.
KEY: (a) Ultrasonic defectoscopy; (b) Frequency; (c) Longitudinal; (d) Recorded parameters; (e) Amplitude; (f) Time; (g) Mechanical impedance; (h) Spectral composition; (i) Continuous; (j) Continuous with frequency modulation; (k) Pulse; (l) Conditions of radiation; (m) Ultrasonic; (n) Frequency range; (o) Methods; (p) Resonance; (q) Shadow; (r) Echoes; (s) Impedance; (t) Free oscillations; (u) Sound; (v) Shear; (w) Surface; (x) Type of waves; (y) Expansions; (z) Bend; (aa) Dry; (bb) Contact with lubricant; (cc) Immersional; (dd) Jet; (ee) Contactless; (ff) Methods of realization of contact.

allowing their use to solve problems not solved with the help of low frequency vibrations. However basic properties of elastic high frequency vibrations are described by the same regularities as the properties of vibrations of the sound range, in particular by regularities determining condition of propagation of elastic waves in a solid uniform isotropic medium possessing elastic properties.

What was said leads to the conclusion concerning that by the term "ultrasonic defectoscopy" one should understand the complex of methods of nondestructive control with the help of elastic vibrations of wide frequency range.

At present [92] five such methods are known (Fig. 79) – shadow (in two variants – basic and mirror), resonance echo-method, impedance and the method of free

vibrations. These methods use five forms of elastic waves - longitudinal, shear, surface, bending and normal waves introduced into the regulated article by five methods - contactless, dry, contact, contact with lubricant, jet and immersion. Waves are radiated in one of three conditions: continuous, continuous with frequency modulation, or pulse. In the control process five parameters are analyzed - amplitude of vibrations, their phase, frequency, transit time, and input impedance of system.

Not one of the known methods of nondestructive control possesses such a large number of variables of parameters. Use of these parameters in different combinations conditions wide possibilities of ultrasonic defectoscopy and huge advantages of it over other methods of nondestructive control.

The assortment of articles and materials controlled by methods of ultrasonic defectoscopy and the list of defects detected by them are very extensive. In articles from magnetic and nonmagnetic, metallic and nonmetallic (porcelain, rubber, plastic, plywood) materials and their different combinations, surface and internal defects are revealed having volume, plane, linear, or point character and constituting disturbance of continuity, heterogeneity of grain and structure, zone of damage of intercrystallite corrosion, and also disturbance of diffusion cohesion, bonding, soldering etc., i.e., practically any disturbance of continuity of acoustical characteristics of controlled material. One should specially note the possibility of very exact measurement of geometric dimensions of articles for one-sided access and also determination of physical characteristics of materials (for instance elastic and other properties) according to measurement of rate of propagation and attenuation factor of elastic oscillations.

Basic tendencies of development of ultrasonic defectoscopy are determined by necessity of further expansion of assortment of controlled articles by increase of objectivity, reliability and productivity of control.

In connection with this, further improvement of methods of radiation and method of UZK of different types of their introduction in the controlled article of observation and registration of results of control, estimate of dimensions of revealed defects, and also development of setups and constructions of instruments allowing this highly productive control is necessary.

2. Radiation and Reception of Ultrasonic Vibrations

In ultrasonic defectoscopy for radiation and reception of UZK piezoelectric converters are usually used, constituting a plate specially prepared from single-crystal quartz, lithium sulfate, Seignette's salt, and also from synthetic crystals of barium titanate, lead zirconate titanate, and others.[1] Characteristics of these materials are given in Table 2. If a piezoelectric plate is compressed or pulled in a specific direction, it is polarized and on its surfaces appear charges whose sign is determined by direction of deformation, and magnitude is determined by applied pressure. This phenomenon is called the piezoelectric effect and is considered in detail in special literature [95-100].

In static conditions piezoelectric effect, for instance for a quartz plate of X-cut, deformed in thickness, is described by the expression

$$U = E \cdot d = g_{11} P d, \tag{1}$$

where U — potential difference appearing between surfaces of plate of piezoelement, E — electric field strength in plate, d — thickness of plate, P — pressure acting on surface of plate, and g_{11} — piezoelectric constant of pressure, characterizing properties of material of piezoelement.

Reverse piezoelectric effect appears in the circumstance that in the piezo-element, upon introduction of it into an electrical field, elastic stresses appear in accordance with intensity and direction of field, as a result of which the piezoelement is deformed. Magnitude of elastic stress (or pressure) in static conditions

$$T = P = e_{11} \frac{U}{d} = e_{11} E, \tag{2}$$

where T — elastic stress, U — potential difference applied to surfaces of plate of piezoelement, P — pressure on surface of plate, d — its thickness, E — electric field strength, and e_{11} — piezoelectric constant of material of piezoelement.

If on the piezoelement there acts variable pressure, changing by defined law,

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[1]Piezoelectric properties, as was first shown by A. V. Shubnikov [101], are also possessed by different anisotropic materials — complex inorganic, complex and organic compounds; however, as yet they have not gained practical use as UZK emitters and collectors.

Table 2. Physical Characteristics of Basic Materials Utilized for Radiation and Method of Ultrasonic Vibrations

Material	Cut	Density $\rho \cdot 10^{-3}$ kg/m^3	Rate of propagation of elastic vibration $c \cdot 10^{-3}$ m/s	Specific wave impedance $\rho c \cdot 10^6$ kg/m^{2}s	Temperature of Curie point t°_{Cu}, °C	Dielectric constant ε	Frequency factor $K \cdot 10^{-3}$ m/s	Young's modulus $E \cdot 10^{10}$, N/m^2	Piezoelectric constant e, N/V·m	Piezoelectric constant of pressure $g \cdot 10^3$, V·m/N	Piezoelectric modulus $d \cdot 10^{12}$, m/V	Piezoelectric constant of deformation $h \cdot 10^{-9}$, V/m	Coefficient of electromechanical bond K, %	High quality Q	Limiting mechanical stress $P_{max} \cdot 10^{-6}$, N/m^2
Quartz	0° X	2,65	5,74	15,4	550	4,5	2,87	8,6	e_{11} 0,17	g_{11} 57	d_{11} 2,3	h_{11} 4,8	10	10^6	95
Seignette's salt[1]	45° Y	1,77	2,4	4,3	45	9,4	1,2	1,0	e_{36} $_{25}$ 0,11/0,08	g_{36} $_{25}$ 160/600	d_{36} $_{25}$ 11/55	h_{36} $_{25}$ 1,6/1,9	29	10^3	14
Lithium sulfate	0° Y	2,06	5,46	11,2	75	10,3	2,73	6,2	e_{22} 0,9	g_{22} 190	d_{22} 16	h_{22} 9	38	10^3	15
Barium titanate	—	5,5	5,68	31,2	100	1200	2,84	18,0	e_{33} 16,7	g_{33} 12	d_{33} 150	h_{33} 1,2	50	400	80
Lead zirconate titanate	—	7,0	5,0	35,0	350	1200	2,5	20,0	e_{33} 16,7	g_{33} 33	d_{33} 33	h_{33} 1,7	50	400	80
Lead metaniobate	—	5,8	2,76	16,0	550	225	1,38	0,46	e_{33} 4,8	g_{33} 40	d_{33} 165	h_{33} 1,2	42	11	—

[1] Radiation and reception of shear vibrations.

then on surfaces of piezoelement appears alternating voltage, changing by the same law.

Correspondingly, if to the piezoelement is applied an alternating electric field, the piezoelement is deformed by the same law, i.e., in piezoelement appear forced oscillations with frequency of the applied alternating voltage.

When frequency of variable pressure or electrical voltage acting on the plate coincides with natural frequency of vibrations of plate, i.e., when it is excited to resonance frequency, amplitude of alternating voltage on surfaces of piezoelement, or correspondingly, amplitude of variable of deformation of piezoelement A_r, increases as compared to amplitude A_s upon excitation to a frequency far from resonance or static conditions.

Growth of amplitude of vibrations at resonance, usually called resonance excess, equals

$$\frac{A_r}{A_s} = \frac{8}{\pi^2} \cdot Q \approx 0.8Q, \tag{3}$$

where Q — so-called mechanical quality of piezoelectric converter, characterizing effectiveness of its work as an oscillatory system in conditions of radiation and reception.

Let us indicate that the quality of a piezoelectric converter abutting the surrounding medium depends on relationship of specific wave impedances of material of converter $\rho_n c_n$ and the media surrounding it.[1] If the converter is surrounded by a medium with specific wave $\rho_1 c_1$, its quality, without taking into account internal losses, will be possible to express so:

$$Q = \frac{\pi}{2} \frac{\rho_n c_n}{2\rho_1 c_1} = \frac{\pi}{4} \frac{\rho_n c_n}{\rho_1 c_1}. \tag{4}$$

If on one side of the converter is located a medium with specific wave impedance $\rho_1 c_1$, and on the other — $\rho_2 c_2$, quality will be expressed by the formula

$$Q = \frac{\pi}{2} \cdot \frac{\rho_n c_n}{\rho_1 c_1 + \rho_2 c_2}. \tag{4a}$$

[1]Specific wave impedance of a medium, as will be shown below, equals the product of density ρ of medium by rate c of propagation of elastic vibrations in it.

In the particular case when specific wave impedance of one of the media is equal to zero (for instance, one surface of the converter borders a vacuum, or, which is practically the same, with air) the formula obtains the form:

$$Q = \frac{\pi}{2} \cdot \frac{\rho_{II} c_{II}}{\rho_I c_I}. \tag{4b}$$

From the last relationship it follows that quality of a converter radiating to one side is twice as high as during bilateral radiation.

Excited by applied alternating voltage, the piezoelement radiates elastic vibrations into the surrounding medium and creates in it a wave field which is characterized (for a homogeneous isotropic medium — liquid, gas) by the following quantity:

a. Displacement of vibrating particles of medium with respect to position of rest:

$$a = A \sin \omega (t - \varphi) \text{ м}, \tag{5}$$

where a — instantaneous value of displacement; A — amplitude of displacement, m; $\omega = 2\pi f$ — angular frequency 1/s; t — time, s; φ — phase constant.

b. Vibration rate of particles, whose peak value is equal to

$$v = \omega A \text{ m/s} \tag{6}$$

c. Acceleration of vibrating particles, peak value of which is

$$B = -\omega^2 A = -\omega v \text{ m/s}^2 \tag{7}$$

d. Density of energy of elastic wave, i.e., mean value of total energy in volume unit:

$$\bar{E} = \frac{1}{2} \rho \omega^2 A^2 = 2\pi \rho f^2 A^2 = \frac{1}{2} \rho v^2 \text{ kg/m}\cdot\text{s}^2 \text{ (or N/m}^2\text{)}, \tag{8}$$

where ρ — density of medium kg/m^3.

e. Intensity of oscillations or force of sound

$$I = \bar{E}c = \frac{1}{2} \rho c \omega^2 A^2 = \frac{1}{2} \frac{\rho c}{\omega^2} B^2 = \frac{1}{2} \rho c v^2 \text{ kg/s}^3\text{, or W/m}^2. \tag{9}$$

f. Acoustic power, i.e., energy transferable by elastic wave in a unit of time through area S of wave front in the direction of its propagation:

$$W=\int IdS \text{ kg}\cdot\text{m}^2/\text{s}^3, \text{ or W.} \tag{10}$$

g. Sound pressure, whose peak value (for a plane wave) equals

$$P=\omega\rho cA=\rho cv \text{ kg/m}\cdot\text{s}^2. \tag{11}$$

If pressure is evenly distributed over area S of the oscillatory system then on this area acts force F = PS. Ratio of the magnitude of this force to magnitude of oscillation speed

$$Z_m=\frac{F}{v} \text{ kg/s} \tag{12}$$

is called the mechanical resistance of the oscillatory system.

Ratio of magnitude of sound pressure to magnitude of oscillation speed in a given point of the medium, called the acoustic impedance, determines magnitude of radiation resistance and power radiated into the medium, and also characterizes bond of radiator with medium.

Pressure and oscillation speed can not coincide in phase, as occurs, for instance, on the surface and near a pulsating sphere radiating a spherical wave. In this case acoustic impedance (total drag) Z of the medium is the complex value consisting of active R and reactive jX components:

$$Z=R+jX. \tag{13}$$

Acoustic power radiated into a medium is proportional to resistance R.

Reactance jX characterizes the part of energy which periodically passes from radiator into medium and back. If reactance composes a considerable fraction of impedance, the radiator works ineffectively — a large part of the energy of the radiator is not transmitted into the medium.

In a plane wave propagating in an infinitely extended medium there is no phase shift between pressure and oscillation speed, and impedance is a real magnitude equal to specific wave impedance of the medium:

$$Z_0=\frac{P}{v}=\rho c \text{ kg/s}\cdot\text{m}^2 ; \tag{14}$$

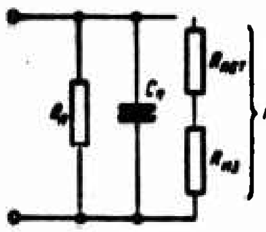

Fig. 80. Equivalent diagram of piezoelectric radiator: $R_{\text{п}}$ — resistance losses in converter; $C_{\text{п}}$ — electrical capacitance of converter; $R_{\text{пот}}$ — resistance losses in load; $R_{\text{из}}$ — resistance of radiation; $R_{\text{м}}$ — full mechanical load impedance.

Expressions (12) and (14) are full analogs of Ohm's law. Therefore the unit of mechanical resistance having the $kg\cdot s^{-1}$ is sometimes called a "mechanical ohm" (mechohm),[1] and specific wave impedance of the medium is measured in mechohm/m^2.

For purposes of ultrasonic defectoscopy it is important to know acoustic power of oscillations introduced into the controlled body. Exact calculation of this power is very complicated and requires calculation of all factors characterizing work of a piezoelectric converter as a quadripole of gyrator type, calculation of complex character of load impedance, and determination of all elements of the equivalent diagram.

The equivalent diagram of a piezoelectric converter fluctuating over thickness on resonance frequency is shown in Fig. 80.

Calculation of acoustic power of oscillations introduced into a controlled body leads to determination of total power radiated by converter under certain conditions of excitation and the consumed full mechanical resistance $R_{\text{м}}$, and to calculation of the fraction of this power (net power) given to resistance of radiation $R_{\text{из}}$.

For practical calculations it is possible with acceptable accuracy to consider that, for instance, during a study in water or with rigid connection (gluing) of converter with surface of solid body of sufficiently large dimensions a plane wave is radiated and consequently the medium is a resistive load characterized by the magnitude of its specific wave impedance.

Acoustic power of a radiator working in continuous conditions can be in this case determined [77] from expression

$$W = \frac{3.55\cdot 10^{-12}\rho_0 c_0 e_{11}^2\cdot f^2\cdot Q_{\text{п}}\cdot U^2\cdot S_{\text{п}}}{\rho_{\text{п}}^2 c_{\text{п}}^4}\ \text{kg-m}^2/\text{s}^3 \qquad (15)$$

where W — acoustic power radiated by a fluctuating piezoelement into the surrounding

[1]The term "mechanical ohm," just as "acoustic ohm," cannot be recognized as successful — according to All-Union Government Standard 8849-58 these terms are not recommended for application.

medium; ρ_0 — density of medium kg/m^3; c_0 — rate of propagation of elastic oscillations in medium m/s; e_{11} — piezoelectric constant of material of piezoelement N/V·m; f — frequency of oscillations 1/s; $Q_\text{м}$ — mechanical quality of piezoconverter; $S_\text{п}$ — area of radiating surface of piezoconverter, m^2; U — amplitude of exciting voltage, V; $\rho_\text{п}$ — density of material of piezoelement, kg/m^3; $c_\text{п}$ — rate of propagation of elastic oscillations in material of piezoelement m/s.

We note that the resulting expression is unfit for direct determination of power radiated into a solid body through a film of contact liquid, as frequently occurs in conditions of ultrasonic control, since the load is not purely active. In similar cases the force with which the piezoconverter is pressed to surface of article affects thickness of layer of contact lubricant, possessing known flexibility. This leads to change of reactive component of load impedance, affecting its input impedance and the quality of piezoconverter, and consequently also radiated power.

As can be seen from the given formula, effectiveness of work of piezoconverter in considerable degree is determined by its mechanical quality, depending on design features of holder. For the most effective work of the piezoconverter it is necessary to ensure high electrical efficiency (i.e., transmission of considerable fraction of electrical energy from generator to piezoconverter) and high acoustic efficiency (i.e., transmission of a considerable fraction of energy of elastic oscillations of piezoconverter into the surrounding medium). Electrical efficiency is determined by relationship of internal resistance of generator and equivalent electrical resistance of piezoconverter, which depends on parameters of the actual piezoconverter and on acoustic load, i.e., on the product of specific wave impedance of surrounding medium on area of plate. The nearer the values of resistances of generator and piezoconverter, the greater the fraction of electrical energy fed to the piezoconverter which will be converted into energy of elastic oscillations, i.e., the higher the acoustic efficiency. However, as can be seen from the diagram Fig. 80 not all energy of elastic oscillations generated by the piezoconverter will be given off to the external load $R_\text{н}$ in the form of acoustic energy. Part of this energy of elastic oscillations will be given off to the actual piezoconverter on resistance losses in the form of thermal energy.

Acoustic efficiency $\eta_\text{ак}$ is determined by the following relationship:

$$\eta_{ак} = \frac{W_{ак}}{W_{эл}} = \frac{R_{из}}{R_{н}} = \frac{R_{из}}{R_{из}+R_{пот}} = \frac{1}{1+\dfrac{R_{пот}}{R_{из}}}. \qquad (16)$$

Here $W_{ак}$ — acoustic energy introduced into controlled body;

$W_{эл}$ — electrical energy consumed by piezoconverter;

$R_{из}$ — resistance of radiation characterizing fraction of energy consumed by external load;

$R_{н}$ — full resistance of load.

From the given formula one may see that $\eta_{ак}$ drops with increase of ratio $\frac{R_{пот}}{R_{из}}$.

At constant amplitude v of rate of oscillation on surface of piezoconverter acoustic power is expressed by the formula

$$W_{ак} = \frac{v^2 R_{из}}{2} \ \mathrm{kg{\cdot}m^2/s^3} \qquad (17)$$

which is completely analogous to the formula for determination of electrical power at assigned current intensity. From the given formula it follows that acoustic power radiated by piezoconverter is proportional to resistance of radiation.

Resistance of radiation can be determined from the expression

$$R_{из} = Y^2 \rho_0 c_0 S_{п}, \qquad (18)$$

where Y — conversion factor of gyrator, equal to

$$Y = \frac{d}{2e_{11}S_{п}}. \qquad (19)$$

Hence

$$R_{из} = \frac{d^2\rho_0 c_0 S_{п}}{4e_{11}^2 S_{п}^2} = \frac{d^2\rho_0 c_0}{4e_{11}^2 S_{п}} = \frac{\rho_0 c_0}{f^2 \cdot S_{п}} \cdot \frac{c^2}{16e_{11}^2} \ \Omega \qquad (20)$$

The quantity $\frac{c^2}{16\,e_{11}^2}$ is characteristic of material of piezoelement, and permits comparing resistance of radiation of different piezoconverters under identical conditions. From formula (20) it follows that for a given piezoelement, resistance of radiation is proportional to specific wave impedance of medium, inversely proportional to area of radiating surface and square of frequency. Therefore at an assigned power of oscillations radiation of piezoconverter in gases is minute; in liquid it is considerably larger, and in metals (under the condition of rigid

bond of surface of vibrating piezoelement with surface of metal) it is the greatest.

It is necessary, however, to note that in conditions of ultrasonic defectoscopy, acoustic power radiated by piezoconverter is usually determined not according to assigned amplitude of oscillation speed but according to known amplitude U of voltage exciting the piezoconverter. In this case acoustic power is more conveniently determined in electrical magnitudes from the expression completely analogous to the expression for determination of electrical power at assigned voltage:

$$W_{ak} = \frac{U^2}{2R_{ms}} \text{ W} \tag{21}$$

From the formula it follows that acoustic power is inversely proportional to resistance of radiation (in this formula it is expressed in electrical units).

Between given formulas (17) and (21), from which it follows that acoustic power in one case is proportional and in the other is inversely proportional to resistance of radiation, there is no contradiction, since one should consider that oscillation speed is proportional to applied voltage and is inversely proportional to resistance of radiation.

For ultrasonic defectoscopy it is possible to consider that acoustic power radiated by piezoconverter on resonance frequency in controlled article with increase of value of specific wave impedance of material of article drops according to a hyperbolic curve (curve a in Fig. 81). With decrease of resistance of radiation to zero, power of oscillations, however, does not increase ad infinitum, as had to be in accordance with formula (21). Increase of power is limited for a small magnitude of resistance of internal losses of piezoconverter (at high quality) by mechanical strength of plate, and at a considerable magnitude of these losses (at low quality of piezoconverter) by increase of fraction of energy of elastic oscillations given to resistance losses in the form of heat (curve b in Fig. 81).

For instance, high quality of quartz plate vibrating in vacuum is very high (hundreds of thousands). Even small electrical power consumed on excitation of vibrations of plate leads to the circumstance that the amplitude of these oscillations attains large values and causes in the plate stresses exceeding strength of crystal. Therefore a quartz plate vibrating in vacuum can be destroyed under comparatively small intensity of acoustic oscillations, equal to several thousand watts per squáre meter.

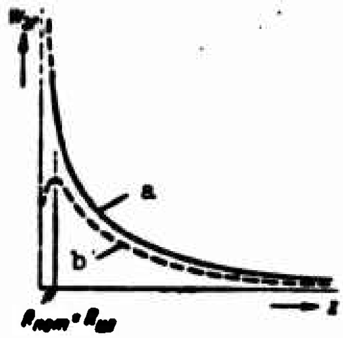

Fig. 81. Dependence of acoustic power radiated by piezoelectric converter on specific wave impedance of medium.

If, however, the quartz plate is placed in water, then inasmuch as the Q of the plate in this case is 8, amplitude of oscillations corresponding to crushing stresses will be attained only at an intensity of oscillations near 2×10^7 W/m^2 [102].

The Q of barium titanate is considerably lower than for quartz – in air it is 400. Metaniobate of lead has an even lower Q – 11. This means that upon excitation of oscillations in plates from these materials, a considerable part of energy is turned into heat and causes strong heating of the piezoelement even at comparatively low intensity of oscillations.

Maximum on curve b (Fig. 81) corresponds to equality of resistance of internal losses of piezoelement and resistance of radiation. Acoustic efficiency of converter is 0.5. In real converters utilized in ultrasonic defectoscopy, resistance of internal losses, as a rule is much less than resistance of radiation and efficiency is higher than 50%.

The power radiated by converters utilized in ultrasonic defectoscopy is very small. For instance, in continuous conditions at one-sided radiation in water a quartz plate of X-cut and area $S_{п} = 3$ cm^2, excited by alternating voltage of amplitude U = 700 V on frequency 2.5 MHz issues an acoustic power of W ≈ 4 W.

Work of a piezoelectric converter in the reception regime is determined by the above formula (1) from which it follows that electric field strength of a field excited in a piezoelement is proportional to sound pressure acting on its surface, depends on its piezoelectric characteristics, and does not depend on area of its surface.

Formula (1) characterizes work of converter in static conditions, and makes it possible to determine idling voltage $U_{хол}$.

For ultrasonic defectoscopy, however, the basic interest is not idling ($U_{хол}$), voltage, but voltage $U_{вх}$, proceeding to the grid of the first tube of the receiving-amplifying channel (Fig. 82). Exact calculation of input voltage is sufficiently complicated; it is necessary to consider the conversion factor of mechanical

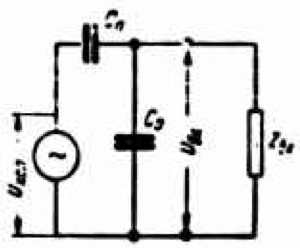

Fig. 82. Equivalent circuit of piezoelectric receiver: $U_{\text{хол}}$ – voltage developed by converter in the idling regime; $C_{\text{п}}$ – electrical capacitance of converter; C_0 – input capacity of receiving-amplifying channel; $U_{\text{вх}}$ – voltage on input of receiving-amplifying channel; $z_{\text{вх}}$ – full input impedance of receiving-amplifying channel.

oscillations into electrical in examining the piezoelectric converter as a quadripole of gyrator type, and also to consider given mechanical impedance of converter, impedance losses formed by electrical capacitance of converter, and input impedance of receiving-amplifying channel.

Voltage $U_{\text{вх}}$, appearing on electrodes of piezoconverter in oscillatory conditions and fed resonance input of receiving-amplifying channel can be [103] determined from the expression

$$U_{\text{вх}} = U_{\text{хол}} \frac{C_{\text{п}}}{C_0 + C_{\text{п}}} \cdot Q_{\text{п}} \cdot Q_{\text{вх}}, \tag{22}$$

where $C_{\text{п}}$ – electrical capacitance of converter; C_0 – input capacity of receiving-amplifying channel; $Q_{\text{п}}$ – mechanical Q of converter; $Q_{\text{вх}}$ – Q of input circuit of receiving-amplifying channel.

For a converter from quartz, whose dielectric constant is small ($\varepsilon = 4.5$), usually $C_{\text{п}} \ll C_0$, and the formula has the form:

$$U_{\text{вх}} = U_{\text{хол}} \frac{C_{\text{п}}}{C_0} Q. \tag{22a}$$

For a converter from barium titanate, whose dielectric constant is very great ($\varepsilon = 1200$), inasmuch as $C_{\text{п}} \gg C_0$, it is possible to consider

$$U_{\text{вх}} \approx U_{\text{хол}} \cdot Q. \tag{22b}$$

In the technology of ultrasonic defectoscopy frequently piezoconverters are used in which the same piezoelement in turn executes the function of radiator and receiver UZK. In this case in selection of material of piezoelement one should consider the constant determining its work as radiator and receiver of oscillations.

A characteristic of material of piezoelement is the ratio of amplitude of voltage $U_{\text{•}}$, appearing on its electrodes under the action of variable pressure of amplitude P to the amplitude of exciting voltage $U_{\text{•}}$, which should be applied to piezoelement in order to create on its surface the same pressure P.

From expressions (1) and (2) for quartz of X-cut it follows that:

$$P = \frac{e_{11}U_r}{d} = \frac{U_n}{g_{11}d}$$

whence

$$\frac{U_n}{U_r} = e_{11}g_{11},$$

i.e., the ratio of voltage is equal to the product of piezoelectric constant e_{11} by piezoelectric constant of pressure g_{11}.

If one were to consider that these constants are connected with other characteristics of material of piezoelement — constant of deformation h_{11} and piezoelectric modulus d_{11} through elastic modulus E, namely:

$$e_{11} = d_{11}E;\ g_{11} = \frac{h_{11}}{E},$$

then it is easy to notice that

$$\frac{U_n}{U_r} = e_{11}g_{11} = d_{11}h_{11} = K^2, \tag{23}$$

where K — coefficient of electromechanical bond characterizing material of piezoelement for converter of combined type.

If separate converters are used, it has meaning to select different materials for radiating and receiving converter. Here can be obtained a value of the product $e_{11}g_{11}$ many times larger than for a combined converter.

In ultrasonic defectoscopy piezoelectric converters working in conditions of free and forced oscillations are used. If a converter works in conditions of forced oscillations on one frequency, to increase sensitivity of equipment this frequency should coincide with natural frequency of converter as a mechanical system. The converter may be considered as a system controlled by resistance, and therefore it is desirable to increase Q in all possible ways. This is recommended in converters working in continuous conditions. However, if the converter works in pulse conditions, an increase of Q involves an increase of duration of transition processes. In order to bring duration of transition

processes to minimum, in the majority of constructions of converters Q is artificially lowered by means of damping, which, of course leads to lowering of sensitivity.

In a number of cases converters are used for work in a relatively wide range of frequencies (usually within the limits of one to two octaves). In connection with this, with the purpose of obtaining a more uniform frequency-response curve natural frequency of the converter is chosen outside the working range of frequencies. Depending upon whether natural frequency of the converter lies higher or lower than working range, the converter will constitute a system controlled by elasticity or mass. In the first case it is required to decrease mass of system, which leads to lowering of its mechanical strength, or flexibility of the system, which leads to lowering of sensitivity of equipment on all frequencies due to decrease of amplitude of displacement. In the second case it is required to increase mass or flexibility of the system, which is connected with constructive difficulties.

Resonance phenomena can be weakened also by increasing resistance of system; however such a system controlled by resistance will possess very low sensitivity.

3. Propagation of Ultrasonic Vibrations

A vibrating piezoelement for sufficiently large dimensions (d) in comparison with length of elastic wave (λ) creates in the surrounding medium a wave field (Fig. 83) having near the radiator an approximately cylindrical form (near zone, zone of Fresnel diffraction), and starting from certain distance (z_0), obtaining the form of a frustum of a cone with small angle 2α at the apex (distant zone, zone of Fraunhofer diffraction).

Thus, waves radiated by the piezoelement propagate as a narrow, slightly divergent, beam. For radiators having the form of a disk and a square directivity is characterized by relationships:[1]

$$\sin\alpha = 1{,}22\frac{\lambda}{D} \text{ (disk)}, \tag{24}$$

[1]If the radiator is rectangular the diagram of directivity does not have symmetry; angle α will be different in different planes; for a plane parallel to one side a rectangle, angle α is determined as for a square with corresponding side.

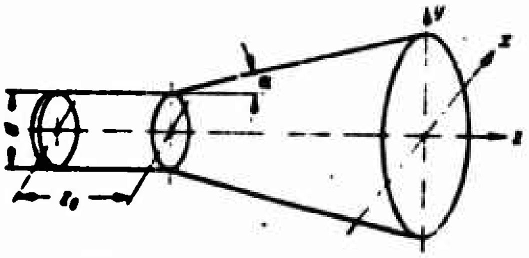

Fig. 83. Schematic image of form of field for disk radiator.

$$\sin\alpha = \frac{\lambda}{a} \text{ (square)}, \qquad (24a)$$

where α — angle between axis of UZK beam, i.e., half the angle of divergence; λ — wavelength; D — diameter of radiator; a — side of square.

Narrow beams of ultrasonic waves, due to their high directivity, may be called beams especially as their propagation observes the laws of geometric optics (more exactly, geometrical acoustics).

Amplitude of oscillations of particles exponentially decreases with removal from radiator. There are two causes of the decrease. First – geometrical divergence, leading to increase of area of wave front: in a cylindrical wave – in proportion to distance from radiator and in a spherical wave – in proportion to the square of this distance. In an ideal plane wave there is no geometric divergence and area of wave front is not changed. However, even in this case in a real medium amplitude gradually decreases with increase of distance from radiator. This is conditioned by the second cause – presence of losses in medium (showing, of course, both in spherical and in cylindrical waves), leading to gradual damping of oscillations during their propagation and connected with power consumption of wave on displacement of particles of medium.

Attenuation factor δ, one of the most important acoustical characteristics of a medium, is determined in the following way:

$$\delta = \frac{1}{x - x_0}\ln\left(\frac{A_0}{A}\right) = \frac{1}{2(x - x_0)}\ln\left(\frac{I_0}{I}\right)\ \frac{\text{neper}^1}{\text{cm}} \qquad (25)$$

where A_0 and A – amplitudes of displacement, and I_0 and I – intensity of oscillations in sections x_0 and x, i.e., at x cm from beginning of reading.

Knowing the attenuation factor, one can determine amplitude of displacement and intensity of oscillations in any section from the relationships:

$$A_x = A_0 e^{-\delta x}. \qquad (26)$$

$$I_x = I_0 e^{-2\delta x}. \qquad (26a)$$

[1]The attenuation factor can be expressed also in decibels per centimeter (dB/cm); 1 decibel = 0.115 neper.

Damping of oscillations is determined first of all by losses on internal friction and appears in gradual absorption of energy of elastic oscillations with transition into thermal.

Absorption in the first approximation is characterized by the Q of the medium and increases with its decrease. If absorption in pure aluminum ($Q \approx 10000$) is taken as unity, in magnesium and cobalt it will be approximately 2, in steels — from 2 to 5, in fused quartz — 2.5 tungsten — 3.5, molybdenum and glass — 5, copper — 36, nickel — 72, polystyrene — 200, organic glass — 400, rubber — 1200.

During propagation of elastic oscillations in a polycrystalline medium possessing elastic anisotropy (for instance, in metal), there is also gradual energy dissipation of oscillations by crystallites, which leads to additional decrease of intensity of oscillations in direction of propagation of wave.

In this case damping is determined by the sum of losses on absorption and scattering of vibrations.

In conditions of ultrasonic defectoscopy of metals, especially of coarse-grained metals, scattering of elastic oscillations leads to structural reverberation.[1] Appearance of structural reverberation oan be explained by anisotropy of elastic properties of crystallites of the metal. Basic considerations on role of dimensions of crystals, anisotropy of their elastic properties, and frequency of UZK, set forth below, were first formulated by the author in 1940 [104, 105].[2] Late in 1948, S. Ya. Sokolov [107] expressed the same thought in general form. Then Mason, McSkimin [108] and Roth [109] in works carried out sufficiently strictly and checked experimentally, for the first time tried to give a quantitative account of damping UZK in metals. Further, I. M. Lifshits and G. D. Parkhomovskiy [110, 111] thoroughly analyzed processes of scattering and absorption and proposed formulas for calculation of corresponding coefficients, considering transformation of longitudinal UZK into shear vibrations, and finally L. G. Merkulov [112, 113]

[1]Reverberation is the result of flutter echo of sound from surfaces limiting volume of space in which sound spreads. In conditions of ultrasonic defectoscopy, during propagation of elastic vibrations in polycrystalline medium (in metal) along with volume reverberation (flutter echo of oscillations from edges of controlled article) structural reverberation is possible also (flutter echo and scattering by boundaries of grains of metal). For small dimensions of article volume reverberation prevails, and with small dimensions structural reverberation prevails.

[2] See also D. S. Shrayber. Application of ultrasonic vibrations for detection of defects in metallic articles. Dissertation, MAI, 1942.

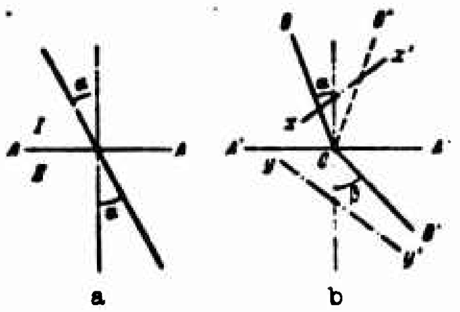

Fig. 84. Influence of anisotropy of medium on conditions of propagation of UZK.

investigating in detail scattering UZK propagating in a polycrystalline solid body, executed a series of calculations and essentially developed the theory of this question.

In the above works the author originated from the idea of two solid media I and II, divided by boundary AA (Fig. 84a). If moduli of normal elasticity E_I and E_{II} and density ρ_1 and ρ_2 of these media is absent, UZK incident on boundary AA from medium I at an angle α, will pass through the boundary without refraction and reflection since rate of propagation of UZK (c_1 and c_2) and also specific wave impedance of both media ($\rho_1 c_1$ and $\rho_2 c_2$) are equal to

$$c_1 = c_2;\ \rho_1 c_1 = \rho_2 c_2.$$

The picture essentially changes in the presence of anisotropy. Let us assume that direction of maximum elastic modulus $E_{I\ max}$ in the first medium is characterized by vector xx', and $E_{II\ max}$ in the second by yy' (Fig. 84b). Then UZK, propagating in the first medium in direction BO with rate c_1, which is determined by the value of E_I for this direction, during transition through $A'A'$ changes speed to c_2, different from c_1 and determined by the value of E_{II}, in the direction of continuation of beam BO (densities ρ_1 and ρ_2 as before are equal to one other). Consequently, there will take place refraction (UZK in the second medium will propagate in direction OB', different from continuation of beam OB[1]) and reflection ($\rho_1 c_1 \neq \rho_2 c_2$), accompanied by appearance of beam OB''. Refractive and reflective indices UZK are determined by degree of anisotropy, characterized by the ratio $\frac{E_{max} - E_{min}}{E_{max}} \cdot 100\%$. With increase of value of this ratio, the fraction of reflected energy increases due to increase of reflectivity, and in a number of cases also because of complete internal reflection of UZK when they hit the boundary of crystallites at an angle

[1]Strictly speaking, direction of the refracted beam will not be rectilinear: the beam of UZK diverges, therefore, due to distinction of rate of propagation of oscillations in direction of axis of beam and the outmost beams when the structure is coarse-grained refraction should be observed: the beam will be distorted in the direction of the vector characterizing direction of minimum value of elastic modulus.

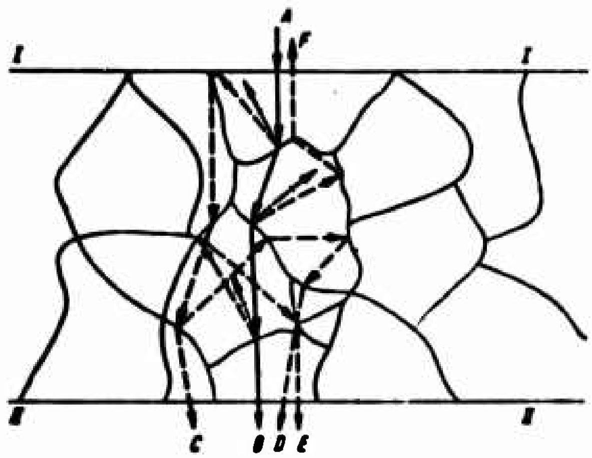

Fig. 85. Diagram of propagation of UZK in a polycrystalline solid body.

exceeding critical angle Φ.

It is possible to affirm thus that during propagation of longitudinal UZK in a polycrystalline medium (for instance, in metal) with disorderly orientation of crystals whose dimensions are comparable with wavelength, in the presence of sufficiently great anisotropy of elastic properties of these crystals there will be observed reflection of UZK from boundaries of crystals, refraction upon transition through boundaries, and gradual dispersion in all sides. All this should lead to corresponding lowering of sensitivity.

A possible picture of passage of UZK through metal is shown in Fig. 85. This picture should naturally be considered only as a very rough diagram. In ultrasonic beam, incident at point A normally to surface I-I encounters on the way differently oriented crystallites, is refracted upon transition from one crystallite to another, as a result its rectilinear path is somewhat distorted and the beam attains surface II-II at point B.

Besides, due to reflection on boundaries of crystallites the UZK penetrate neighboring crystallites and after flutter echo and refraction attain surface II-II or return to surface I-I, emerging from metal in points C, D, E and F. These oscillations, due to considerable difference of movement in metal, differ in amplitude and phase.

As a result there is created a complicated wave field consisting of the primary beam and a great number of repeatedly reflected beams which are combined with the primary beam and interfere with it and with each other.

It is possible to imagine the case, when in the presence of a defect on the path of the primary beam AB for point B there are revealed vibrations caused by total action of beams C, D, and E, as a result of which in place of an acoustical shadow a penumbra is obtained.

The case is possible when in the absence of a defect on the path of beam AB the field near point B can be weakened as a result of interference of primary beam

Table 3. Influence of Degree of Anisotropy of Elastic Properties of Metals on Conditions of UZK Propagation

Metal	A		B	Conditions of propagation of longitudinal UZK			Б		B	Conditions of propagation of shear UZK		
	$E_{max} \cdot 10^{-10}$, N/m²	$E_{min} \cdot 10^{-10}$, N/m²	$\frac{E_{max} - E_{min}}{E_{max}}$ 100%	$R_{L(max)}$, %	$n_{L(max)}$	φ_L	$G_{max} \cdot 10^{-10}$, N/m²	$G_{min} \cdot 10^{-10}$, N/m²	$\frac{G_{max} - G_{min}}{G_{max}}$ 100	$R_{S(max)}$	$n_{S(max)}$	φ_S
W	40	40	0	0	1,0	90	15,5	15,5	0	0	1,0	90
Mg	5,14	4,37	15	0,16	1,08	68	1,84	1,71	7	0,03	1,02	80
Al	7,7	6,4	17	0,2	1,1	65	2,9	2,5	14	0,15	1,08	68
Ti	14	9,8	30	0,6	1,16	58	—	—	—	—	—	—
U	29	14	52	3,35	1,44	44	—	—	—	—	—	—
Fe-α	29	13,5	54	3,6	1,47	43	11,8	6,1	48	2,6	1,39	46
Ni	30	12	60	5,1	1,58	39	—	—	—	—	—	—
Ag	11	4,4	62	5,85	1,63	38	4,45	1,97	56	4,0	1,5	42
Au	11,4	4,2	63	5,88	1,65	37	4,1	1,8	56	4,0	1,5	42
Cu	19,4	6,8	65	6,5	1,7	36	7,7	3,1	60	5,15	1,57	40
Cd	8,3	2,88	65	6,5	1,7	36	2,51	1,84	27	0,57	1,17	58
Zn	12,63	3,56	72	9,5	1,88	32	4,97	2,78	40	2,25	1,34	48

Note: A – elastic modulus, Б – shear modulus, B – degree of elastic anisotropy.

with multiple reflected beams arriving with phase shift.

In control by echo method a repeatedly reflected pulse, emerging from point F creates the impression of presence of defect located at a depth equal to total length of path of pulse in metal and capable of exceeding thickness of controlled article.

The fraction of scattered energy will be determined mainly by the ratio of length of elastic wave to average dimension of crystallite and also degree of anisotropy of metal. Knowing maximum and minimum values of elastic modulus [114, 115], it is possible to calculate maximum reflectivity of UZK passing through the boundary of two differently oriented crystallites, maximum refractive index and magnitude of critical angle of total internal reflection. Approximate values of enumerated parameters are given in Table 3. They give an idea about influence of elastic anisotropy of crystallites of metal on scattering of UZK, and permit placing metals according to degree of anisotropy in a series starting from tungsten – a metal with zero anisotropy – and finished by metals for which elastic anisotropy and consequently also coefficient of scattering UZK are sufficiently great.

As a result of major works of the above authors, theory of scattering of elastic waves in polycrystalline medium can be considered as formulated sufficiently

strictly. It considers the degree of elastic anisotropy of metal, relationship between length of elastic wave and average dimension of crystallite, and effect of transformation of longitudinal waves into shear waves during scattering of longitudinal waves. Formulas proposed on the basis of theory permit calculating scattering coefficients UZK and obtaining results agreeing sufficiently well with experimental results. Comparison of scattering coefficients calculated by L. G. Merkulov for iron, copper and magnesium with obtained experimental data confirms the position of these metals in the series given in Table 3.

Formulas given by L. G. Merkulov for scattering coefficients of longitudinal and shear UZK by crystals of cubic and hexagonal systems show that scattering depends on many factors and increases by complex law with increase of frequency of UZK, overall volume of the crystallite and degree of its anisotropy.

Coefficient of scattering of ultrasonics γ for the shown pure metals at frequencies for which ratio of length of elastic wave λ to average linear dimension of crystallite $\bar{D}$ is larger than ten can be, according to L. G. Merkulov, approximately determined from the expression $\gamma \approx \bar{D}^3 f^4$. For higher frequencies or for a bigger grain, where $\lambda/\bar{D} < 8 - 10$, $\gamma \approx \bar{D} f^2$.. At further decrease of ratio $\lambda/\bar{D}$, when it becomes less than four scattering obtains a diffuse character and coefficient of scattering decreases. Experiments conducted by the author on aluminum, zinc, and iron completely confirm what was said [116].

All considerations because of structural reverberation, stated above, pertain to a single-phase system (pure metal, uniform solid solution).

The phenomenon essentially is complicated during propagation of UZK in polyphase system. In this case one should additionally consider influence of elastic properties of carbide, intermetallide and other precipitations, their relationship with elastic properties of crystallites of solid solution and their anisotropy.

As L. G. Merkulov and L. A. Yakovlev showed [117], during investigation of electroporcelain, scattering of UZK by small particles of second phase evenly distributed in a uniform solid medium is proportional to average volume of particles, relative contents of dispersing phase, and coefficient considering relationship of elastic characteristics of scatterer and environment is proportional to the fourth power of frequency and inversely proportional to the fourth power of rate of propagation of UZK.

Comparison of data on absorption and scattering of UZK in different metals permits explaining the observed essential impairment of conditions of control of articles from nickel of copper and their alloys and also from alloyed steels (especially the austenitic class), as compared to articles from aluminum and its alloys. Not less important than damping the acoustic characteristic of a medium is rate of propagation in it of elastic waves of different types.

In gases and liquids rate of propagation of longitudinal waves is determined by the expression

$$c_L = \sqrt{\frac{1}{\rho \cdot \beta_{ад}}} = \sqrt{\frac{\varkappa}{\rho \cdot \beta_{из}}}, \qquad (27)$$

where $\beta_{ад}$ — adiabatic compressibility; $\beta_{из}$ — isothermal compressibility; γ — adiabatic coefficient; ρ — density of medium.

In solid bodies rate of propagation of elastic waves depends on type of wave, and for a given type of wave also on dimensions of the body in which it propagates.

For a rod whose transverse dimensions are considerably less than wave length rate c_L of propagation of longitudinal waves (more exact than expansion waves) equals

$$c_L = \sqrt{\frac{E}{\rho}}, \qquad (28)$$

where E — Young's modulus; ρ — density of medium.

In an unbounded medium conditions of propagation of longitudinal waves are different, inasmuch as during deformation any volume element experiences resistance of the surrounding medium, which is equivalent to increase of elasticity. Elasticity of a solid unbounded medium is characterized by two parameters — Young's modulus E, and Poisson's ratio σ. Rate of propagation of longitudinal waves in an unbounded medium is expressed therefore by a more complicated formula:

$$c_L = \sqrt{\frac{E}{\rho} \cdot \frac{1-\sigma}{(1+\sigma)(1-2\sigma)}}. \qquad (29)$$

For the majority of metals the value of Poisson's ratio fluctuates within the limits 0.25-0.35. As a result values of rate of propagation of longitudinal waves in an unbounded medium exceed values of rate of their propagation in a rod from the same material approximately by 10-25%.

With increase of ratio of diameter of rod to wave length, the rate does not increase monotonically but changes by complicated law. Thus, at $d \approx \lambda$ minimum of rate is observed, equal to approximately one third of the rate for an unbounded medium, and at values $\frac{d}{\lambda}$ within the limits 1.6-2.2 propagation of longitudinal waves cannot be recorded at all.

Rate of propagation of shear waves in an unbounded medium (c_S) is determined by the expression

$$c_S = \sqrt{\frac{G}{\rho}}, \tag{30}$$

where G — shear modulus, whose magnitude for the majority of metals, as is known, composes 0.38-0.4 of the magnitude of Young's modulus.

Taking into account what was said, rate of propagation of shear waves in an unbounded medium composes approximately 0.62-0.64 of the rate of propagation of purely longitudinal waves.

Surface waves (Rayleigh waves) propagate with a rate determined by the relationship

$$c_R = \frac{0,87+1,12\sigma}{1+\sigma}\sqrt{\frac{G}{\rho}}, \tag{31}$$

from which it follows that this speed composes ~0.92-0.93 of speed of propagation of shear and ~0.57-0.59 from speed of propagation of longitudinal waves.

Speed of propagation of bending waves is determined by frequency of oscillations, and besides, depends on form and dimensions of body in which these waves propagate. Thus for an infinitely long rod of radius r, speed is equal to

$$c_B = \frac{\pi r}{\lambda}\cdot\sqrt{\frac{E}{\rho}} = \sqrt{\pi r f}\cdot\sqrt[4]{\frac{E}{\rho}}, \tag{32}$$

and for an infinite plate of thickness d, composes

$$c_B = \frac{\pi d}{\lambda\sqrt{3}}\sqrt{\frac{E}{\rho}\cdot\frac{1}{1-\sigma^2}} = \sqrt{\pi d f}\sqrt[4]{\frac{E}{\rho}\cdot\frac{1}{3(1-\sigma^2)}}. \tag{33}$$

Speed of propagation of normal waves, just as bending waves, is determined by frequency of oscillations and thickness of article, and besides, is distinguished for every type and order of normal wave. Therefore, for instance, the angle of incidence of a longitudinal wave, from which as a result of transformation a normal wave appears and which one should choose in accordance with its speed, is determined according to the curve depicting dependence of this angle on product of frequency of oscillations by thickness of article.

Dependence of speed of propagation of normal waves on frequency of oscillations, i.e., dispersion of speed, has essential value, especially during work with short pulses. Propagation of frequency components of a pulse with different speeds leads to gradual distortion of form of initial pulse. Rate of displacement of maximum of bending waves or group speed of propagation of a pulse differ from phase speed of propagation of UZK of different frequencies composing the pulse.

For ultrasonic defectoscopy specific wave impedance of medium, characterizing resistance rendered by an infinitely extended medium propagating the wave has large value. If the medium is not infinitely extended, it is necessary to consider active mechanical resistance (internal friction) of the oscillatory system in the direction of propagation of elastic oscillations and in the direction perpendicular to it, and then impedance is expressed by a complex value (acoustic impedance). If active losses (which is not always permissible) are disregarded, wave impedance Z is expressed by the real part of acoustic impedance and can be recorded in the following way:

$$Z = \sqrt{\frac{m_1}{c_1}}, \qquad (7?)$$

where m_1 and c_1 – linear, i.e., happening per unit length mass and correspondingly flexibility of system.

From this expression it follows that in a system not possessing active losses, wave impedance has purely active character. It is necessary, however, to stress that the active character of wave impedance is not connected with irreversible thermal losses of energy of oscillations, and appears in the circumstance that during propagation of a travelling elastic wave in a system not possessing active losses, every section of the system completely removes energy from the preceding

and thus completely without loss and reflections transmits it to the following section.

The above expression for wave impedance may be written otherwise, expressing linear mass through density of medium and area of cross section, and linear flexibility through Young's modulus and area of cross section $m_1 = \rho S$ and $c_1 = \frac{1}{ES}$.

Then

$$Z = \sqrt{\frac{m_1}{c_1}} = \sqrt{E\rho S^2} = S\rho\sqrt{\frac{E}{\rho}} = S\rho c_L,$$

whence specific wave impedance of the medium

$$Z_0 = \rho c_L. \tag{35}$$

Thus specific wave impedance of a medium not possessing active losses is expressed by the product of density of medium by speed of propagation in it of elastic oscillations of given type.

In Table 4 are given the most important acoustic characteristics of different substances.

From this table one may see that speed of propagation of longitudinal oscillations in gases composes in most cases 300-400 m/s (only for hydrogen does it equal 1285 m/s), for liquids the values of speed lie within the limits 1000-1500 m/s, and for the majority of solid bodies speed composes 4000-6000 m/s with separate deflections to smaller values (rubber — 1480 m/s) and to larger values (beryllium — 12,250 m/s).

With such values of propagation rates of oscillations and at the frequencies utilized in defectoscopy wavelengths are minute.

Damping in air is very great; in water it is three orders less. In plastics, resins, rubber, ebonite, textolite, wood damping is approximately of the same order as in air and is determined basically by absorption. In casting from high-alloy steel, aluminum and magnesium alloys, by cast-iron, copper, brass, bronze, in porous ceramics, and in minerals damping is approximately the same but is determined mainly by scattering.

In casting from low-alloy steels, of aluminum and magnesium alloys, of highly durable cast iron, in half-finished products from deformed copper alloys, and in

articles from ceramic metal damping is one-two orders lower.

Damping in deformed iron, aluminum, magnesium, silver, titanium, tungsten, zirconium, and alloys on that base and also in glass, quartz, and porcelain is an order still lower — at 2.5 MHz it is only little more than in water and with increase of frequency increases by a complicated law.

4. Phenomena Observed on Interface of Media

Specific wave impedances of gases of liquids and metals are related approximately as 1:3000:100,000 and attain for metals very large values (see Table 4)

Such relationships of specific wave impedances is very fortunate for the purpose ultrasonic defectoscopy, using the significant reflection of ultrasonic oscillations from the surfaces of defects in a metal, which in the majority of cases can be considered as the metal-air interface.

If a flat elastic wave propagating with speed c_1 in a uniform medium with density ρ_1 reaches the boundary with a second medium with density ρ_2 and speed of propagation of wave in it c_2, there occurs partial reflection of energy. If it is considered that the second medium is infinite and damping of elastic oscillations is disregarded, then, as was shown above, values of specific wave impedance can be expressed by real quantities. The reflection factor with respect to amplitude of pressure shift (i.e., ratio of corresponding amplitudes in reflected and incident waves) is equal to

$$V = \frac{P_{\text{отр}}}{P_{\text{пад}}} = \frac{A_{\text{отр}}}{A_{\text{пад}}} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}. \qquad (36)$$

In general, however, the second medium has finite extent and possesses damping, therefore the reflection factor with respect to amplitude is determined by relationship of acoustic impedances of both media, and consequently is a complex quantity characterizing besides the ratio of amplitudes of reflected and incident waves also the phase jump appearing upon reflection from interface of media.

From expression (36) it follows that the reflection factor can be positive or negative. Thus if wave impedance of the second medium is less than the first, the reflection factor will be negative. This signifies that phase of shift and pressure in a reflected wave will lag the incident by a half period (antiphased

Table 4. Basic Acoustical Characteristics of Different Substances

Substance	$c_{\text{пр}}$ m/s	$c_{\text{п·п}}$ m/s	$c_{\text{п·м}}$ m/s	$\rho \cdot 10^{-3}$ kg/m^3	$\rho c_{\text{пр}} \cdot 10^{-4}$ kg/m^2 s	$\delta_{\text{пр}}$ Np/cm (f = 2.5 MHz)
Aluminum	6260	3080	2800	2,7	1700	0,002—0,05
Babbit	6800—7300	4000—4700	—	11—15	7700—10200	—
Beryllium	12250	8200	7870	1,85	2260	—
Tungsten	5160	2870	2650	19,1	10420	—
Iron	5850	3230	3000	7,7	4560	0,01—0,08
Gold	3240	1200	—	19,3	6260	—
Brass	4430	2120	—	8,1	3610	—
Lithium	3000	—	—	0,53	160	—
Magnesium	4600	2200	—	1,7	780	0,001
Copper	4700	2260	2100	8,9	4180	0,018—0,044
Molybdenum	6290	3350	3110	10,09	6350	—
Nickel	5630	2960	—	8,8	4950	—
Niobium	4100	1700	—	8,6	3530	—
Aluminum oxide	10000	—	—	3,9	3900	—
Tin	3320	1670	—	7,3	2420	—
Platinum	3960	1670	—	21,4	8460	—
Mercury	1450	—	—	13,6	1900	0,006
Lead	2160	700	660	11,4	2460	—
Silver	3600	1590	—	10,5	3800	—
Titanium	6000	3500	2790	4,5	2700	—
Uranium	3300	—	—	18,7	6200	—
Zirconium	4900	2900	—	6,5	3200	—
Cast iron	3500—5600	2200—3200	—	7,2	2500—4000	—
Araldite	2500	1100	—	1,18	300	—
Quartz, single-crystal along the X axis	5740	3140	—	2,6	1400	—
Quartz, fused	5570	3515	3390	2,2	1300	—
Porolon	1800—2000	—	—	1,1—1,2	200—270	—
Polystyrene	2670	1120	—	1,1	300	0,23
Rubber	1480	—	—	0,9	140	2,5
Glass silicate	5500	3420	—	2,7	1500	0,006
Plastic	2550	1300	—	1,18	300	0,58
Textolite	2920	—	—	1,28	375	—
Teflon	1350	—	—	2,2	300	—
Porcelain	5300—5900	—	—	2,4	1300—1400	—
Ebonite	2400	—	—	1,2	290	—
Water	1490	—	—	1	149	0,001
Glycerine	1920	—	—	1,26	250	0,06
Oil, transformer	1400	—	—	0,9	125	—
Air	335	—	—	$1,3 \cdot 10^{-3}$	0,043	1

reflection). And, conversely, if $\rho_2 c_2 > \rho_1 c_1$, reflection will be cophasal, i.e., phase of displacement and pressure in incident and reflected waves coincide. Inasmuch as pressure on both sides of interface of media must be identical, pressure near the interface in the second medium $P_{\text{пр}}$ is equal to sum of pressures in incident $P_{\text{пад}}$ and reflected $P_{\text{отр}}$ waves on the interface, i.e., $P_{\text{пад}} + P_{\text{отр}} = P_{\text{пр}}$.

It follows from this that during passage of elastic waves from a medium with

a smaller to a medium with a greater wave impedance pressure in passing wave (near the interface) will be more than in the incident (transmission coefficient with respect to pressure $D=\frac{P_{\text{пр}}}{P_{\text{пад}}}>1$); during propagation of elastic wave in the opposite direction pressure in passing wave is less than in incident ($D < 1$).

Reflection factor with respect to energy (i.e., fraction of reflected energy), determined by ratio of intensities in incident and reflected waves, under the condition of perpendicular fall of ultrasonic oscillations on an infinite interface is a real quantity and is equal to

$$R=\left(\frac{\rho_2 c_2-\rho_1 c_1}{\rho_2 c_2+\rho_1 c_1}\right)^2. \tag{37}$$

From the metal-air interface elastic oscillations are practically completely reflected since specific wave impedances differ by approximately 100,000 times. For the metal-liquid interface the reflection factor is ~80%. If, however, ratio of specific wave impedances is 2-2.5, only 15-20% energy is reflected.

Let us consider the general case of elastic waves striking perpendicularly to the surface layer of a medium of thickness d with acoustic impedance Z_2. The layer divides uniform media with acoustic impedances Z_1 and Z_3.[1] During propagation of a wave from a third medium into the first the reflection factor with respect to amplitude is equal

$$V=\frac{V_{23}+V_{12}e^{2jk_2d}}{1+V_{23}V_{12}e^{2jk_2d}}, \tag{38}$$

where $V_{12}=\frac{Z_1-Z_2}{Z_1+Z_2}$, $V_{23}=\frac{Z_2-Z_3}{Z_2+Z_3}$ – reflection factors (with respect to amplitude) on interfaces of media 2.1 and 3.2 correspondingly; k_2 – wave number for medium 2, equal to $\frac{2\pi}{\lambda_2}$ (λ_2 – length of elastic wave in medium 2).

After simple transformations the expression for reflection factor with respect to energy can be obtained:

$$R=\frac{Z_2^2(Z_1-Z_3)^2+(Z_1Z_3-Z_2^2)^2+(Z_2^2-Z_3^2)(Z_1^2-Z_2^2)\cos\alpha}{Z_2^2(Z_1-Z_3)^2+(Z_1Z_3-Z_2^2)^2+(Z_2^2-Z_3^2)(Z_1^2-Z_2^2)\cos\alpha}. \tag{39}$$

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[1]Disturbance of continuity in a solid body, forming an air gap or a plate immersed in liquid constitute a particular case for which $Z_1 = Z_3$.

from which can be obtained the calculation formula:

$$R = \frac{a - \cos\alpha}{b - \cos\alpha}, \tag{40}$$

where a and b — numerical coefficients whose value, are determined by the relationship of Z_1, Z_2 and Z_3 (for the case when $Z_1 = Z_3$, $a = 1$), and $\alpha = \frac{4\pi d}{\lambda_s}$.

Acoustical transmission of system is equal tc $D = 1 - R$.

Analysis of the given calculation formula shows that R and D are periodic functions of the ratio $\frac{d}{\lambda_s}$. Outer limits of this function correspond to the value $\alpha = 0$. This signifies that maximum reflection ($R_{max} = \frac{a + 1}{b + 1}$) is obtained when there is an odd number of quarter wave in the space and maximum transmission is $D_{max} = 1 - \frac{a - 1}{b - 1}$, when the space is equal to zero or a whole number of half-waves.

The condition of maximum transmission, expressed in the fact that in the thickness of the considered layer is a whole number of half-waves, signifies appearance of resonance in this layer, leading to a sharp decrease of acoustic impedance of the layer as an oscillatory system inasmuch as reactive component of impedance becomes equal to zero.

Dependence of impedance on entrance of oscillatory system ("input impedance") on wavelength of this system also is used in ultrasonic defectoscopy.

When it is necessary to transmit energy of ultrasonic oscillations from one solid body into another the inevitable air gap between surfaces of both bodies causes considerable reflection and therefore should be excluded. Energy transfer of ultrasonic oscillations, as already was indicated, usually is carried out through liquid, for instance by means of submersion of both bodies in a bath (immersion method) or by applying a film of lubricant (contact method with lubricant), or finally, through a flowing stream of liquid (jet contact). Acoustical low frequency oscillations can be transmitted also through a dry contact. A layer of liquid, for instance, transformer oil, applied on the surface of a solid body fills the gap, as a result of which a sufficient fraction of energy of ultrasonic oscillations can be transmitted.

In Fig. 86 are given curves of dependence of acoustical transmission of different layers (water, transformer oil, air, film of aluminum oxide) between hard

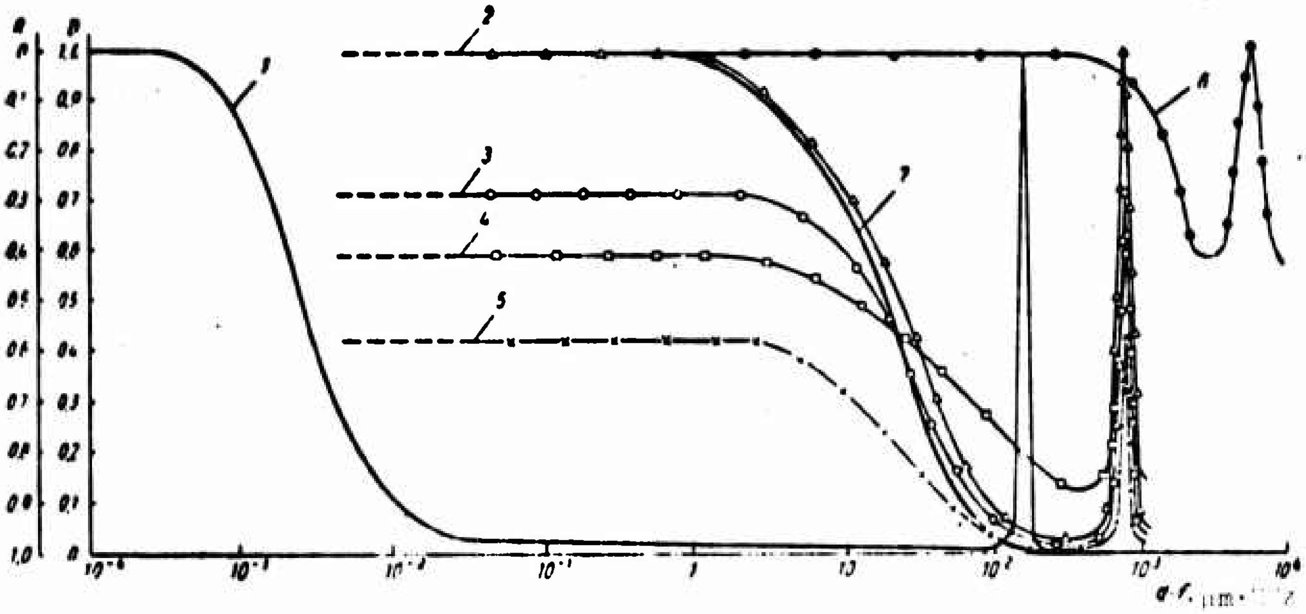

Fig. 86. Dependence of D and R on frequency of UZK f and on thickness d of layer between two media: 1 – steel-air-steel; 2 – quartz, aluminum, beryllium-liquid (oil, water) – aluminum; 3 – quartz, aluminum-liquid (oil water) – steel; 4 – quartz, aluminum-liquid (oil water) – plastic; 5 – quartz-liquid (oil water) – tungsten; 6 – aluminum-aluminum oxide-aluminum; 7 – quartz-oil-aluminum (experiment).

media on thickness of layer and frequency of ultrasonic oscillations.[1]

One may see that at assigned frequency of ultrasonic oscillations transmission of system drops rapidly with increase of gap. Thus for a quartz-oil-aluminum (or steel) system a sharp fall of transmission starts at ~25 μm·MHz. For frequency 2.5 MHz magnitude of gap is equal 10 μm, which approximately corresponds to degree of surface finish of surface (∇6). The curve for a steel-air-steel system testifies to the exceptionally high sensitivity ultrasonic defectoscopy, since the most insignificant gaps are practically opaque for ultrasonic oscillations used in defectoscopy of frequencies.

Resonance phenomena giving a sharp increase of transmission practically show no noticeable form during manifestation of defects, inasmuch as in this case they are preceded, as can be seen from the given curves, by a wide zone of minimum (practically zero) transmission.

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[1]Calculation is made for infinitely extended solid bodies. For possibility of using the given curves for determination of transmission of the layer of contact lubricant during energy transfer of ultrasonic oscillations from the search head into the controlled article, see Section VI.

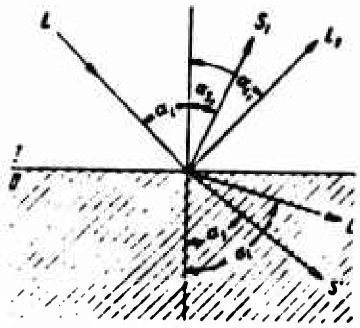

Fig. 87. Reflection, refraction, and transformation of ultrasonic oscillations falling from a liquid or solid medium on the interface with a solid medium (in case of fall from liquid medium, reflected beam S_1 is absent).

Upon considerable increase of thickness of intermediate liquid layer, and in the absence of resonance phenomena (pulse conditions), transmission of system does not depend on frequency and is equal to product of coefficients of transmission of interfaces of media 3.2 and 2.1. Strictly speaking, this is true only for determination of total energy in controlled medium. At sufficiently high frequency or when there is unevenness (roughness) on the surface of this layer, it acts as a scatterer and energy content transmitted in direction of field axis decreases.

If ultrasonic oscillations fall on the interface of two media at an angle different from 180°, along with reflection refraction is observed also, where as in optics the ratio of sines of angles of incidence of reflection and refraction equal the ratio of speed of propagation of oscillations of corresponding form in first and second media.

When longitudinal oscillations strike the liquid – solid body interface at a glancing angle different from 90°, in the liquid will spread a reflected beam (longitudinal oscillations). In a solid body, due to transformation of a refracted beam into longitudinal beams and shear oscillations two beams will be observed proceeding at different angles with speeds determined by type of wave in second medium.

Upon transition of longitudinal elastic oscillations from a solid medium into a solid besides the two beams two reflected beams will be observed also (Fig. 87).

If we increase angle of indidence α_L of longitudinal wave L from liquid or solid medium I into solid medium II, at certain value α_1 (first critical angle) the refracted longitudinal beam L' begins to glance along interface (total internal reflection of longitudinal oscillations), occurs not penetrating the second medium (Fig. 88a).[1] At further increase of angle of incidence to value α_S (second critical angle) total internal reflection will take place also for shear oscillations. Shear oscillations will not appear in second medium (88b).

[1]It is assumed that speed of propagation of oscillations in second medium is more than in the first.

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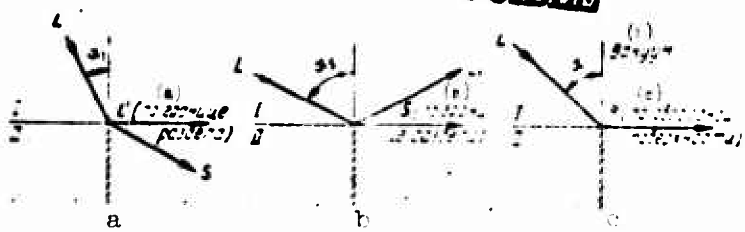


Fig. 88. Total internal reflection of longitudinal – a and shear – b oscillations at incidence on boundary under critical angles and also excitation of surface waves – c.
KEY: (a) interface; (b) vacuum; (c) free surface.

If angle of incidence is increased somewhat further, on the surface of the second medium under the condition that to the right of the point of introduction of ultrasonic oscillations it is free (i.e., borders with a vacuum, or which is practically the same – with air), surface waves appear (Fig. 88c).

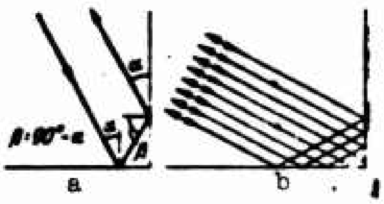


Fig. 89. Reflection of a single beam – a and a beam of ultrasonic oscillations – b from edge of dihedral angle.

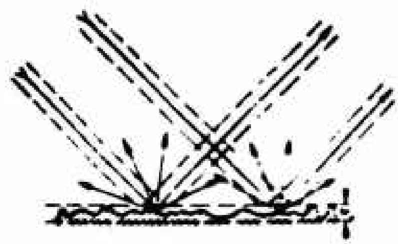


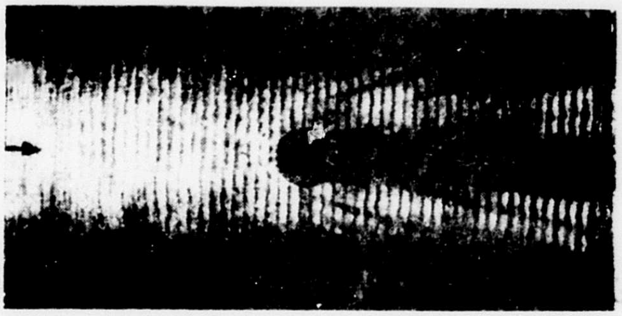
Fig. 90. Diffuse reflection of ultrasonic oscillations from a rough surface.

For defectoscopy along with reflection of ultrasonic oscillations from a plane reflection from right, dihedral, and trihedral angles inside the controlled body is also interesting. A beam of ultrasonic oscillations incident on the edge of a dihedral angle in the plane perpendicular to edges of angle is reflected exactly in the opposite direction (Fig. 89). When a parallel beam of ultrasonic oscillations is incident on the vertex of a trihedral angle from any direction it is reflected exactly in the opposite direction.

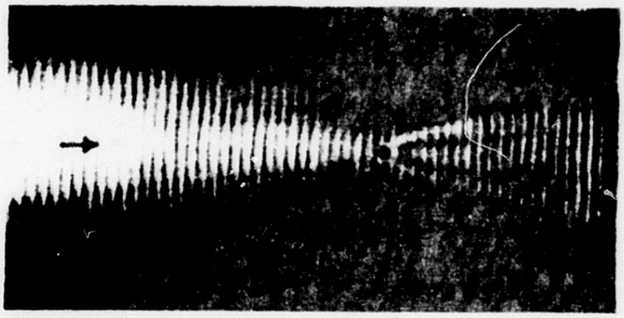
We considered reflection using laws of geometric optics and assuming the interface as smooth (specular reflection). If the interface has an unevenness whose height (δ) exceeds 0.05-0.1 wavelength, which occurs during reflection from a real defect, diffuse reflection is observed (Fig. 90).

5. Diffractional and Interference Phenomena

If during propagation of ultrasonic oscillations they meet an obstacle, depending upon relationship of dimensions of this obstacle and wavelength different diffractional phenomena can be observed. Figure 91a shows the presence of a sound shadow after a cylinder whose diameter of which is 5.5 times more than the wavelength. Such an obstacle gives considerable reflection of oscillations. If dimensions of obstacle are equal to wavelength (Fig. 91b) or less, that beams round the obstacle are somewhat diffused and considerable reflection in this case is not observed.



a



b

Fig. 91. Influence of dimension of obstacle on formation of sound shadow.

In the propagation of elastic oscillations interference plays a large role along with diffraction. This phenomenon occurs as a result of imposition of two or more coherent oscillations, i.e., oscillations having identical frequency (or if frequencies of these oscillations are related as whole numbers) and constant difference of phases.

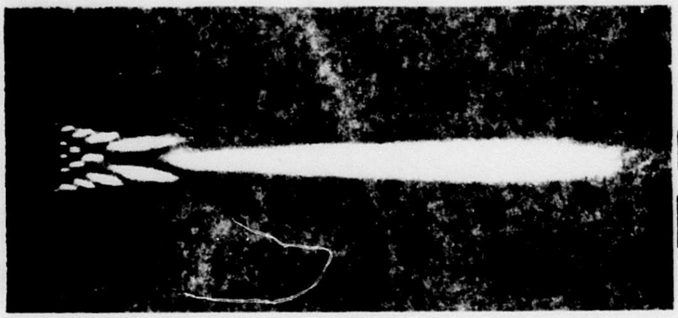


Fig. 92. Structure of wave field of disk radiator of elastic oscillations.

Resultant oscillations in any point of a medium turn out to be equal to the algebraic sum of all oscillations arriving at this point. Amplitude of oscillations of any point can therefore grow if separate oscillations arrive at this point in phase or decrease and even become equal to zero if oscillation arrive in antiphase.

Interference can lead to formation of standing waves, characterized by an alternating point of rest along field axis and by points oscillating with maximum amplitude.

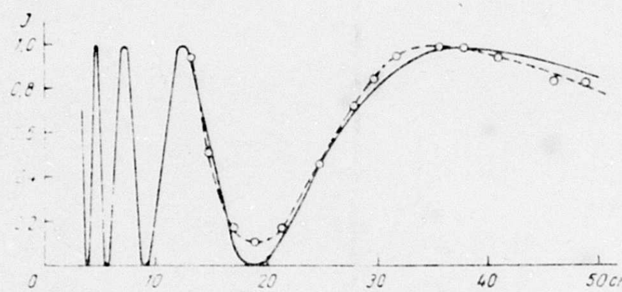


Fig. 93. Intensity of oscillations I on axis of wave field of disk radiator depending upon distance to radiator. Solid curve — calculated, dotted — experiment.

In Fig. 91 interference lines are noticeable along direction of propagation of oscillations, the result of their composition. Owing to interference in a number of points in defined regularity oscillation are absent. Because of this distribution of amplitudes of oscillations in the field of the illuminator, i.e., structure of the field close to the illuminator is quite complicated (Fig. 92). Intensity of oscillations close to the oscillating disk on its axis sharply changes as was shown in Fig. 93. Only starting from a defined distance does change obtain a monotonic character, following the law of inverse proportionality to distance.

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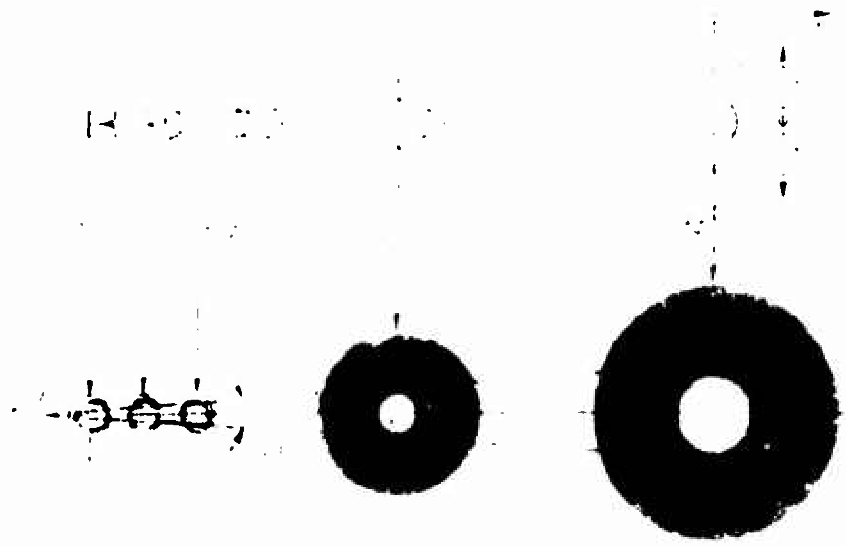

Fig. 94. Distribution of sound pressure in wave field of disk radiator in planes perpendicular to field axis at various distances from radiator: $F_{и}$ – imaginary focus; Φ – extent of Fresnel zone; 2α – angle of divergence of beam.

Pressure measured in planes parallel to radiating surface of disk at small distances from it changes the same way by jumps, and thus only starting from defined distance starts a monotonic drop with removal from field axis (Fig. 94). In accordance with this, as was already said, a near zone of a wave field (zone of Fresnel diffraction) and a distant zone (zone of Fraunhofer diffraction) are distinguished. Extent Φ of the near zone depends on relationship between diameter of radiator D and length of elastic wave λ and for a radiator of piston type can approximately be determined from the expression[1]

$$\Phi = \frac{D^2}{4\lambda} = \frac{S_{п}}{\pi\lambda}, \tag{41}$$

where $S_{п}$ – area of radiator.

It is necessary, however, to note that the picture shown in Figs. 92-94 is accurate only for conditions of continuous radiation of oscillations and for a radiator of piston type having disk form.

[1]Experimental check of the expression, carried out by the author on a real radiator, shows that it gives a correct result if instead of D the value of effective diameter of radiator depending on construction of bracing of piezoelectric element and ~0.7 D is used.

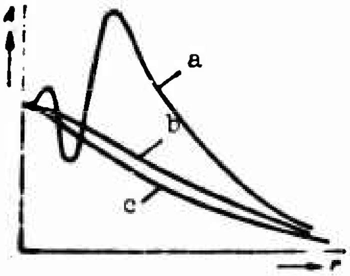

Fig. 95. Dependence of sound pressure A on axis of wave field of disk radiator on distance r to radiator at uniform – a, nonuniform – b excitation of separate sections of radiating surface and during the radiation of pulses which do not exceed one half-period (c).

Nonuniform excitation of a disk radiator in real designs, connected, for instance, with pressing of piezoelectric element along circumference or with independent excitation of separate zones of radiating surface, caused by the form of electrodes on them, another form of radiator – square, right-angles or triangular – or a special form of electrodes on surface of radiator – all this in considerable degree decreases effect of interference [87, 118], smoothing the collapses seen on Fig. 93. Calculations and experiments carried out by the author jointly with A. G. Gorokhov and G. S. L'vov showed that such smoothing occurs during the radiation of short pulses. Moreover, in the limiting case when pulse duration is equal to one half-period the interference zone disappears and change of pressure with distance causes monotonic character starting from surface of radiator (Fig. 95).

This reasoning is accurate not only for structure of field of radiator but also for structure of field in the shadow zone after an obstacle located on axis of radiator and having disk form. Interference phenomena lead to sound pressure after the obstacle not equaling zero in any point on the continuation of this axis, and fluctuates taking different values from minimum, composing a certain fraction of pressure before the obstacle, to those exceeding this pressure. The enumerated measures permit smoothing structure of field in zone of shade. Inasmuch as real defects almost never have correct form, in defectoscopy interference structure of sound shade usually is not observed.

In pulse regime conditions of propagation of ultrasonic oscillations in a medium differ from conditions of a regime of continuous radiation. During propagation of ultrasonic oscillations in the form of short pulses of following one after another through intervals of time at which is ensured full damping of every pulse prior to sending the following, incident and reflected waves do not meet and do not interfere. Ultrasonic oscillations propagate in an oscillatory system of infinite length, where there is no reflected wave, or in a system loaded on resistance equal to wave impedance of system, which also leads to absence of a

reflected wave. In this case input impedance of system is determined by parameters of the actual system. If ultrasonic oscillations are radiated in a continuous regime, with a finite extent of system (practically, for conditions of ultrasonic defectoscopy, when dimensions of controlled article in direction of resounding exceed the length of elastic wave a small number of times) input impedance depends not only on parameters of system but also on frequency of oscillations and on magnitude of load at the end. This dependence effectively is used in certain methods of ultrasonic defectoscopy.

In an oscillatory system along with the above forced oscillations whose frequency is determined by the radiator and does not depend on parameters of system free oscillations excited by impact can also propagate. Free oscillations are fading. Initial amplitude of these oscillations is determined the force from without (force of blow) and frequency and attenuation factor by parameters of the actual system — its mass, flexibility and mechanical resistance. Analysis of the frequency spectrum of free oscillations makes it possible to judge variation of parameters of system and recently has also been used in ultrasonic defectoscopy.

The considered conditions of propagation of ultrasonic oscillations pertain to a uniform, homogeneous, isotropic medium. In real conditions of ultrasonic defectoscopy of metals, as was noted above, there is a structural reverberation which disturbs the reception of the primary signal and limits sensitivity of ultrasonic monitoring.

6. Methods of Ultrasonic Defectoscopy

Ultrasonic defectoscopy can be carried out by five[1] methods:

1. Shadow method (otherwise — method of sound shadow or method of through resounding), in which ultrasonic oscillations as a rule are introduced in an artic[le] on one side and taken from the other (in mirror variant — from the same). Inasmuch as ultrasonic oscillations encountering a defect on the way are reflected in the opposite direction, presence of defect in article can be judged either by decrease

[1]At present there is a sixth method, proposed by Yu. V. Lange (author's certificate No. 161564, USSR, 1962) and called the velocimetric method. This method is based on measurement of change of speed of propagation of normal waves in zone of defects in multilayer constructions, and is carried out with the UVFD-1.

of energy of ultrasonic oscillations in the zone of geometric shadow after the defect, where this energy penetrates only due to diffraction, or by change of phase of ultrasonic oscillations rounding the defect and covering, consequently, a longer path.

2. Pulse echo method, in which ultrasonic oscillation receiver, located on the same side as the radiator receives reflected pulses of ultrasonic oscillation (echosignals) from surface of defect and from opposite edge of the controlled article, allowing detection of different defects in articles of different form and dimensions — including very large.

3. Resonance method, using dependence of input impedance of system on its wavelength. The method permits, determining resonance frequencies of a system, measuring thickness of articles (sheets, pipes, tanks) in the controlled zone (one-side access) and revealing certain defects in this zone.

4. Impedance method, using dependence of input impedance of system on load at the end, which when used in the control of laminar (glued, soldered) constructions permits revealing zone of disturbance of solid bond between the thin external shell (leaf sheathing) and sublayer (metallic, nonmetallic or honeycomb filler).

5. Method of free oscillations, based on analysis of frequency spectrum of free oscillations in a system excited by a blow. This permits monitoring massive laminar constructions for the presence of zones of disturbance of the solid bond between any pair of layers and presence of defects in any of these layers.

III

SHADOW METHOD OF ULTRASONIC DEFECTOSCOPY[1]

1. Physical Bases of Method

If into investigated article 1 (Fig. 96) are introduced ultrasonic oscillations from radiator 2, and if on the path of the oscillations no heterogeneities are met, causing their reflection, receiver 3 located on the opposite side of the article will register passage of ultrasonic oscillations through the article. Intensity of passing [UZK] (УЗК) will be less than intensity UZK introduced into metal inasmuch as when they propagate from radiator to receiver there occur losses connected with reflection, damping and geometric divergence of beam. At constant thickness of article, flat front and rear surfaces, and uniform material the level of intensity UZK incident on the receiver, rigid and coaxial fastened with radiator, will be almost constant, and readings of indicator 4 will insignificantly fluctuate near a certain defined value which should be accepted as initial (Fig. 96a). If, however, on the UZK path heterogeneities are met, then depending upon area of cross section of UZK beam, area of reflecting surface, and distance between defect and rear surface of article, there can be the following variants:

1. UZK beam is completely covered by defect — indicator shows zero (Fig. 96b).

2. Defect reflects clear "sound shadow" to rear surface of article — readings of indicator sharply drop (Fig. 96c).

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[1]Recently this method is frequently called the method of "through resounding," which should be recognized as more correct.

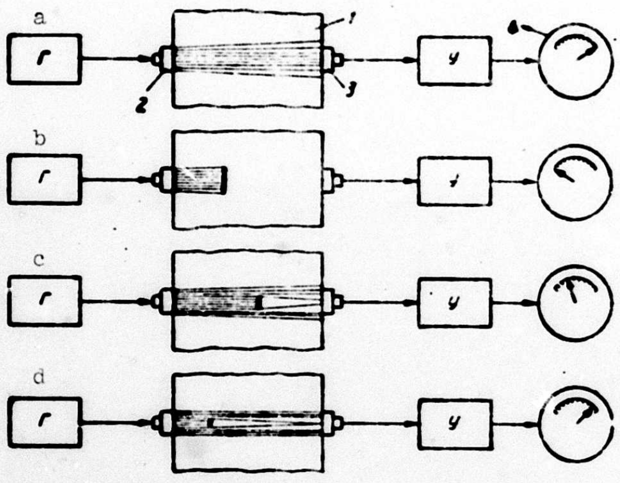

Fig. 96. Shadow method of ultrasonic defectoscopy.

3. Sound shadow, as a result diffraction, does not reach rear surface of article — receiver picks up UKZ whose intensity decreases by the magnitude of energy reflected from defect readings of indicator drop insignificantly (Fig. 96d).

To control by the sound shadow method, in general access to article from both sides is necessary. Introduction of UZK into article can be carried out by contact, immersion or flow method. UZK can be radiated in continuous or pulse conditions. In the last case a very progressive mirror variant of the shadow method can be easily realized. In this case control is conducted with one-side access to article or, at least, with a one-sided location of radiator and UZK receiver.

The shadow method with use of longitudinal UZK radiated in a continuous cut and introduced in article by immersion method was proposed in 1928[1] by S. Ya. Sokolov [119]. Somewhat later in 1931 Mühlhäuser[2] and almost simultaneously Bethenod[3] patented methods for flaw detection in casting, forgings, and welded seams, based on use of "mechanical oscillations of increased frequency," i.e.,

[1] S. Ya. Sokolov. Author's certificate No. 23246, 1928.

[2] O. Mühlhäuser, DRP, 5695, 1931.

[3] J. Bethenod, F. P. 704952, 1931.

UZK. However Bethenod found no practical application for Mühlhäuser's setup.

The first flow detectors were made by S. Ya. Sokolov, who in 1935 published his works containing discriptions of his instruments and methods of investigating metals using UZK.

The instrument of S. Ya. Sokolov, made according to Fig. 97 permits judging presence of defect according to the character of the ripple appearing on surface of oil [122]. UZK, radiated by mosaic quartz radiator 1, are introduced in controlled article 2, located just below surface of tank with transformer oil.

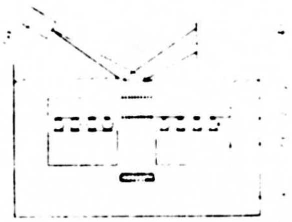

Fig. 97. Diagram of internal flow detection in metal after S. Ya. Sokolov.

The article is placed on balls 6 and can shift over area 5, allowing resounding in different zones. If there are no defects in metal, the UZK with certain loss of intensity pass through article and cause a ripple on surface of oil. Illuminating place where UZK leave on surface of oil by illuminator 3, it is possible to observe the characteristic picture on screen 4 (Fig. 98a): when there is a defect in the metal part of the UZK is reflected and in the metal behind the defect will be formed a sound shadow. As a result character of ripple on surface of oil changes, which will lead to change of picture on screen. It is impossible, however, not to note that a sufficiently clear difference in the picture observed on the screen (in absence and presence of defect) nevertheless is not obtained, in consequence of which confident judgement of quality of controlled metal is very difficult. This is a serious deficiency of the setup (Fig. 98b).

Fig. 98. Ultrasonogram of S. Ya. Sokolov: a — in the absence, b — in the presence of a defect.

Another setup of S. Ya. Sokolov [123], based on use of diffraction of light on ultrasonics, and allowing judgement on intensity of UZK passing through controlled article according to the number of lines of diffractional spectrum, observed on a screen, was used by Muller [124] for control of sets of wheels on cracks in axles under naves.

In 1938 Kruse [125] published an investigation of metals using UZK. As an immersion medium he applied mercury and for measurement of intensity UZK used an arrangement having on the output a vacuum-tube voltmeter. Recording the voltmeter readings as the article is resounded by an ultrasonic beam, Kruse found a sound shadow, indicating presence of defect.

It is necessary to stress that neither distribution of a ripple on the surface of the oil (or a diffraction picture in the instruments of S. Ya. Sokolov and Muller) nor voltmeter readings for Kruse allowed a sufficiently confident judgement about presence or absence of defect. Therefore S. Ya. Sokolov came to the conclusion that creation of a device allowing to observation of an immage of the revealed defect (heterogeneity of metal) on a special screen. In 1935 he proposed [126] a method of observation of heterogeneities of a medium on the screen of a special instrument. In design the instrument resembled a television set of that time. A diagram of the instrument of S. Ya. Sokolov is shown in Fig. 99.

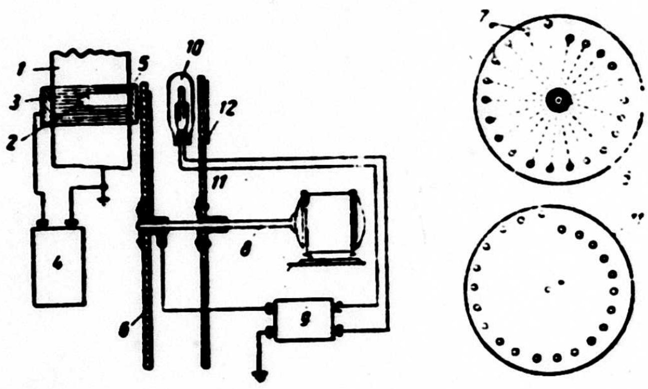

Fig. 99. Diagram of installation of S. Ya. Sokolov, making it possible to obtain image of revealed defect: 1 — controlled article; 2 — cavity; 3 — radiator UZK; 4 — generator; 5 — receiver UZK; 6 — capacitance commutator; 7 — metallic contacts; 8 — common shaft; 9 — amplifier; 10 — neon tube; 11 — Nipkov receiving disk; 12 — frame.

A defect in the investigated article 1 upon resounding reflects its shadow on the surface to which adjoins receiver quartz plate 5. On the surface of this plate appears distribution of charges constituting electrical image of field. The "electrical image" is scanned along short lines by capacitance commutator 6 in the form of a Nipkov disk, through the receiving device is fed to the neon tube and is considered with the help of second disk 11.

Thus, shifting the article between radiator and receiver UZK it is possible to observe sound shadow characterizing presence of defect directly on screen (Fig. 100).

In 1936 Polman[1] [128, 129] patented a method of flow detection in metal allowing direct observation of sound shadow on a special screen which is a unique sound-optical converter.

Fig. 100. Image of sound shade (stream in liquid) obtained on device of S. Ya. Sokolov.

In subsequent years Polman improved this method so much that a reliably effective industrial instrument was created.

The basic advantage of this instrument is the possibility of simultaneous investigation of a considerable area of the article, and, as will be shown below, rather high resolving power.

All these general purpose devices naturally did not consider numerous difficulties appearing during industrial control of important articles. Therefore they did not find wide application.

First works of the author on development of shadow method of ultrasonic defectoscopy were conducted in 1938-1941.

The basic purpose of these works was creation of a method of detection of internal stratifications in blades of propellers forged from aluminum alloys, and also equipment for solution of this problem.

This very complicated problem was impossible to solve with ultrasonic flaw detectors known at that time. For its solution basic conditions of selection of rational parameters of shadow flaw detectors were demanded considering

[1]Polman, R., DRP 741335, 1936.

influence of different factor on propagation of UZK in metal and consequently on indicator readings. These factors include structure of metal, determining level of reverberational noises and consequently real sensitivity of method and also dimensions and form of article, determining degree of influence of interference and refraction of UZK and optimum scheme of scanning and reading.

Analysis of influence of these factors allowed creation of a rational method of control and of reliably effective equipment, designed for work in specific industrial conditions.

Later basic results of works on improvement of the shadow method of ultrasonic defectoscopy [104, 105, 116, 130] and resulting recommendations on rational design of equipment are presented. A considerable part of these positions is used in contemporary Soviet and foreign equipment.

2. Sensitivity of Shadow Method and Method of Control

Sensitivity is the most important characteristic of any method of defectoscopy, making it possible to estimate minimum dimensions of defect revealed by this method in the plane perpendicular to direction of resounding (sometimes this characteristic is called angular resolving power).

Determination of sensitivity of shadow method by means of derivation of fundamental equations connecting minimum dimension of revealed defect with UZK frequency and with depth of embedding of defect was attempted by different researchers including the author even at the end of the thirties. Equations, by analogy with optics, were derived on the basis of beam acoustics for a parallel beam of UZK without proper calculation of wave phenomena playing an important role in relationships between wavelength and dimensions of obstance existing in ultrasonic defectoscopy and determining distribution of energy of oscillations in zone of shade.

Equations proposed by the author [105] in 1941 have the following form:

$$D_{min} = 1{,}57\sqrt{l\lambda};\quad l_{max} = \frac{D^2}{2{,}44\lambda};\quad \lambda_{max} = \frac{D^2}{2{,}44l}. \qquad (42)$$

where D — diameter of defect, λ — length of elastic wave, l — distance from defect to UZK receiver.

Naturally these equations and graphs constructed according to them reflected only the qualitative side of the phenomenon and made it possible to estimate

sensitivity only in the first approximation.

Nonetheless inasmuch as more exact solutions of the problem were not found, the shown graphs were used for appraisal of sensitivity [77, 90].

Additional analysis of influence of different conditions of control on sensitivity of method, made later by the author also on the basis of elementary concepts of beam acoustics, attractive by their simplicity and clarity but with more thorough calculation of wave phenomena, made it possible to definitize somewhat the earlier equation.

Moreover in distinction from the first case formation of shade was considered in more real conditions: a divergent and not a parallel beam UZK fell on the defect.

Figure 101 shows conditions of formation of shade when dimensions of radiator and defect are commensurable (Fig. 101a) and also with a point radiator, located at different distances from defect of finite dimensions (Fig. 101b, c). In the first case zone of penumbra will be formed when there is no point source of penumbra and diameter of shade increases as radiator approaches defect.

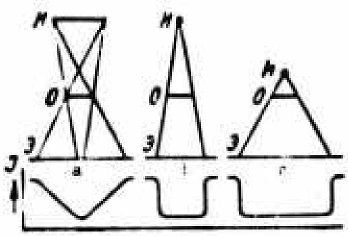

Fig. 101. Conditions of formation of sound shade and penumbra during different relationships of dimensions of radiator and reflector and different distance between them: И — radiator; O — reflector; Э — screen; I — intensity of oscillations in plane of screen.

Obviously the less the diameter of the radiator and distance from radiator to defect, the greater the exactness of projection image of shade of defect, the bigger the diameter of shade and distance from defect to point on the line connecting centers of radiator and receiver of UZK, in which diameter of shade as a result of diffraction becomes equal to zero.

Earlier it was indicated that pressure on axis of wave field of disk radiator as a result of interference sharply changes within limits of Fresnel zone and only a distance equal to $D^2/4\lambda$ from the radiator attains its last maximum value, after which it monotonoically decreases. If we consider that curvature of wave front is small, on the basis of the principle of Babinet it is possible to affirm that in zone of shade after opaque round screen distribution curve of pressures on axis will constitute

inverted image of curve of shown in Fig. 93. Pressure in zone of shade on axis of field is not equal to zero and changes in considerable limits, attains last minimum at $D^2/4\lambda$, from screen, after which it monotonically increases (shadow "swims"). In real conditions, during measurement of pressure by a receiver of finite dimensions when form of defect deviates from a regular circle pressure on surface of receiver is averaged and oscillations of pressure along axis are somewhat smoothed (this is especially noticeable during work in pulse conditions), however general regularity is kept.

Sensitivity of method can be approximately characterized by minimum diameter of the D_{min} defect-reflector, having the form of a regular circle after which a spherical wave of length λ creates a zone of shade ending at point of location of UZK receiver, which is at distance R_0 from defect under the condition that from this point the first Fresnel zone is not noticeable since it is closed by defect. The problem thus reduces to determination of radius of first zone of Fresnel depending upon wavelength λ, distance $R_И$ from point radiator to defect, and distance R_0 from defect to receiver (Fig. 102).

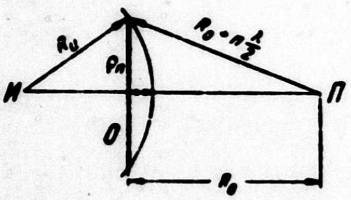

Fig. 102. Calculation of sensitivity of shadow method: И — radiator; П — receiver; О — reflector (defect).

As it is known the radius of any Fresnel zone ρ_n can be calculated by the formula

$$\rho_n = \sqrt{n\lambda \cdot \frac{R_И R_0}{R_И + R_0}}.$$

where n — number of zone; λ — wavelength; $R_И$ — distance from radiator to screen; R_0 — distance from screen to point of observation.

Since n = 1, sensitivity will be determined by the expression

$$D_{min} = 2\sqrt{\lambda \cdot \frac{R_И R_0}{R_И + R_0}}. \qquad (43a)$$

From the equation it follows that sensitivity is increased with decrease of length of elastic wave, distance from radiator to defect, and distance from defect to receiver. Hence can be made the conclusion that sensitivity is maximum at small values of $R_И$ and R_0, i.e., in the control of thin articles, which fully agrees with reality.

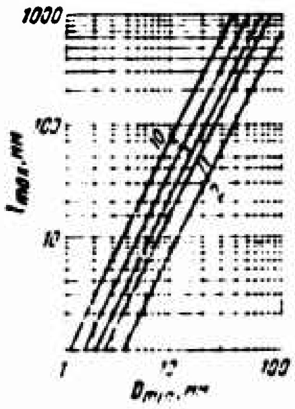

Fig. 103. Minimum diameter of defect detected by shadow method in a flat parallel article of thickness $2l$ at different frequency of UZK. Frequency, MHz, is shown by figures near curves.

The graph built according to this equation is shown in Fig. 103.

Externally it is analogous to the graph to proposed earlier [105] and can be used for approximate appraisal of sensitivity under the condition that $R_{\text{И}} = R_{0}$, for instance, when the defect is at a depth equal to half the thickness of the controlled article and when radiator and receiver are placed on surfaces of article (or at equal distances from these surfaces). As is easy to show:

$$D_{min} = 2\sqrt{\frac{R_0^2\lambda}{2R_0}} = 1.41\sqrt{R_0\lambda}, \quad (43b)$$

which is very close to the earlier formula (42).

It is necessary to note that this condition corresponds to least sensitivity since the value of expression $\frac{R_{\text{И}} R_0}{R_{\text{И}} + R_0}$ is maximum at $R_{\text{И}} = R_0$, if, however, $R_{\text{И}}$ or R_0 (at constant sum, i.e., at $R_{\text{И}} + R_0 = \text{const}$) tend to zero, i.e., if defect is located near front or rear surface of controlled article, sensitivity increases (Fig. 104).

With decrease of dimensions of radiator sensitivity is increased due to formation of a more clear shade analogous to what occurs, for instance, during radioscopy by X-rays where conditions of control are improved by using tubes with "sharp focus," i.e., small diameter of surface emitting the X-rays.

Making a "point" radiator by means of a limiting decrease of dimensions of piezoelectric plates is not advisable due to structural and energy considerations (radiated power decreases). This problem can be solved by using concentrators or by focusing ultrasonic rays emanating from a plate of considerable dimensions. In this case focus of radiator, formed with a special lens will play the role of a "point" radiator of sufficient power. However, since this radiator will possess although small but finite dimensions,

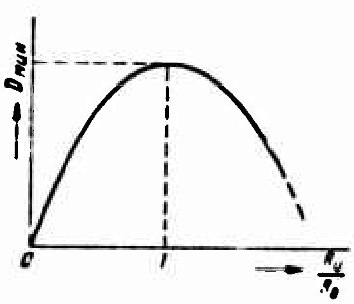

Fig. 104. Sensitivity of shadow method depending upon depth of bedding of defect.

sensitivity will be lower than follows from the given formula.

The receiver of UZK is profitable a point receiver; it will more clearly record boundary of zone of shadow at displacement in the direction perpendicular to axis of field. Therefore in front of the receiver is sometimes placed a diaphragm. However, application of diaphragm leads to increase of distance R_0. Besides, under the influence of the applied pressure only on central zone of receiver of piezoelectric element, visible through hole in diaphragm, charges appearing on electrodes of piezoelement are distributed over the whole area, as a result of which voltage on piezoelectric element drops, i.e., sensitivity of receiver is lowered.

For appraisal of real sensitivity it is necessary to consider yet a series of factors. In calculation we originated from determination of sensitivity threshold with decrease to zero of pressure on surface of UZK receiver placed in region of sound shadow. Meanwhile for detection of defect only a certain minimum "degree of contrast" of field clearly recorded by the indicator is needed, i.e., difference of pressures created by UZK passing through a defective and "healthy" section.

What was said is explained by Fig. 105. Along the axis of abscissas on this diagram is plotted distance from defect in region of shadow. Starting from distance R_0' pressure gradually increases (solid curve), approaching values of pressure in zone not distorted by presence of defect. If in this zone at the same distance pressure is equal to unity, contrast at point R_0' on axis of field also is equal to one. However, if for operation of indicator smaller contrast k is needed, a defect of smaller dimension will be registered whose shadow is shorter, the last minimum will be located at point R_0'' and the logistic curve of pressure will pass through point A (dotted curve). This circumstance leads to essential increase of sensitivity and should be considered by means of introducing into the expression determining sensitivity of the method, contrast ratio k, a magnitude smaller than unity and characterizing minimum contrast still making it possible to record the defect in assigned control conditions.

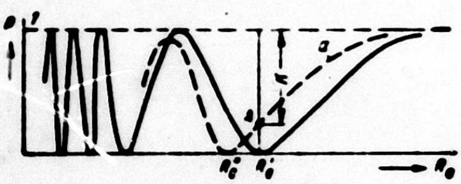

Fig. 105. Calculation of influence of minimum contrast of shadow on sensitivity of shadow method.

On the other hand, formation of sound penumbra or background of defined intensity

is promoted by interferences from structural reverberation, which leads to necessity of introduction of a special arrangement into the flaw detector circuit for "cutoff of noises" as a result of which the indicator reacts to a relatively greater change of pressure than at entrance into region of penumbra. Obviously sensitivity decreases and this decrease can be considered by introducing into the expression for sensitivity of the method the coefficient of reverberation u ($u > 1$), characterizing level of interferences from structural reverberation for a given material.

Finally under the most profitable conditions for control, when thickness of article is maximally small, i.e., at $(R_{\text{п}} + R_0) \to 0$, formula (43a) gives $D_{\min} \to 0$, i.e., sensitivity tends to infinity. This, obviously, is not so — sensitivity threshold in this case is determined by that fraction of effective surface of UZK receiver which it is necessary to shield in order to obtain decrease of its area by k times. If we originate from uniform equal distribution of intensity of UZK in the section of beam passed by the diaphragm (diaphragm is fixed before UZK receiver and diameter 2b), obviously in the formula should be introduced constant component $b\sqrt{k}$.

Taking into account what was said it is possible to write:

$$D_{\min} = b\sqrt{k} + 2ku\sqrt{\frac{R_{\text{п}}R_0}{R_{\text{п}} + R_0}\lambda}. \qquad (44)$$

This expression can be called the fundamental equation of the shadow method. It can serve for appraisal of real sensitivity in different specific cases; however reevaluation of its accuracy does not follow, since during derivation a series of assumptions was made which can essentially distort results. Besides, such factors as power of UZK radiator and damping of UZK in material of article were not considered at all.

Meanwhile for work in conditions ensuring optimum sensitivity of the method power of UZK sent by radiator into article should be correctly selected. Criterion for selection of power must be total losses of energy of oscillations on reflection during passage from contact medium into article and also on damping. Power of UZK attaining the receiving piezoelectric converter should be somewhat higher

than that which is required for maximum reading of indicator.

Thus it becomes clear that it is necessary to carry out a strict derivation of the equation of the shadow method, considering all necessary conditions.

We considered the question about minimum dimension (in plane perpendicular to direction of resounding) of defect revealed by shadow method. We go now to sensitivity of method in the sense that it is understood in X-ray flaw detection. For this it is necessary to determine dimensions of defect in direction of resounding which are its detection. The thinnest defect is stratification. For simplification of calculations we will present stratification in the form of an infinitely extended flat-parallel air layer in metal. For determination of thickness of this layer, ensuring reflection of UZK, Bergmann [77] used the second formula of Rayleigh, which, however, gives a strongly oversized sensitivity.

During calculation by formula (39), derived more strictly, taking into account the fact that impedances of media are expressed by complex values, it is possible to see that coefficient of reflection drops with decrease of thickness of gap: for instance, for an air gap in steel at frequency 3 MHz it is 97% for a thickness of 0.01 μm and 57% for a thickness of 0.001 μm. These data, obtained by the author, as also data of Ye. D. Pigulevskiy [131], by making an analogous calculation will agree better with experimental data. The minimum thickness of the gap below which total transmittance is observed (at 3 MHz) by calculations of Ye. D. Pigulevskiy turned out to be approximately 0.1 μm. Gaps exceeding this give practically 100% reflection.

Experiments carried out by the author show that real sensitivity of the method approximately corresponds to calculated sensitivity. Thus, at 2.5 MHz good reflection of UZK from air gap in steel when gap is about 1 μm thick is obtained. Conditions for obtaining noticeable transmittance obviously are very critical. For this reason (and also because the actual defect in metal does not possess ideally flat and parallel surfaces), with periodic change coefficients of reflection and transmission, depending on ratio of thickness of air gap to length of elastic wave, as should occur according theory practically need not be considered. However the finest stratification and rough cavities clearly are revealed.

Otherwise defects constituting a layer in the form of the finest oxidized

film[1], of deformed slag inclusion, etc., are dealt with. In these cases values of specific wave impedances of layer and surrounding medium differ insignificantly, and therefore a sharp reduction of coefficient of reflection is possible for layers of defined thickness. Let us note one more possible case — presence of a thin liquid or solid layer dividing the two media. Here the case when wave impedance of material of layer is close to mean geometric wave impedances of the media divided by it is possible. The system becomes maximally transmissive, analogously to what is known in optics as the phenomenon of "clearing."

In the control of real metallic articles sensitivity can, however, be lower than calculated values. Lowering of sensitivity can be connected with influence of structural reverberation, with interference phenomena, with refraction of UZK on surface of controlled article, etc.

It is possible to present a series of examples confirming considerations on role of crystal structure and phase composition of metal.

N. F. Otpushchennikov [132] revealed considerable difference in weakening of UZK passing through a steel sample in longitudinal and transverse (with respect to rolling) directions. In the first case weakening was approximately twice less than in the second. This is explained by the presence of oriented structure. Crystallites in a rolled material are stretched along the rolling. When the sample is resounded across the rolling UZK encounter a large number of crystallites and therefore undergo stronger reflection (inclusions of impurities along boundaries of grains promote the same). In certain cases for parallel boundaries of crystallites oriented along the rolling and for sufficiently large dimensions formation of standing waves in crystallites themselves is possible, which also hampers passage.

Conditions of propagation of UZK along rolling are more favorable. Crystals are longer, the number of them per unit of length, and consequently weakening of UZK will be many times less. S. Ya. Sokolov [123] noted propagation of UZK along a copper wire a distance of several kilometers.

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[1]For instance, for a thin film of aluminum oxide lying in aluminum (very important case for practice) calculation gives maximum coefficient of reflection ~40% with sharp fall in wide regions adjacent to values $d = n\lambda/2$ (approximately just as for a plastic plate in water).

Acicular crystals in cast metal, big crystallites of austenitic grain, recrystallized zinc nonmetallic inclusions in steel, lead in lead bronze (especially in liquational zone), graphite in cast iron, carbide and intermetallide deposits in complex structural and heat-resistant alloys strengthen the scattering of UZK. When samples from these materials are resounded is obtained a picture analogous to that obtained during resounding of strongly porous metal. Scattering of UZK decreases with decrease of their frequency; however, sensitivity of control also drops.

The influence of crystal structure and phase composition of resounded material on scattering of UZK leading to considerable structural reverberation, and in the shadow method — to formation of sound penumbra instead of shadow must be considered during development of a shadow flaw detector, providing in its setup a device for removing interference of reverberational noises.

For this purpose in the flaw detector developed by the author in 1940 for control of blades the principle known in radio engineering as noise cutoff (amplitude selection of signals). Receiver with noise cutoff for weak signals is "locked" automatically by different methods ensuring sufficiently sharp limiting of signal on minimum. Switching in of indicator through relay on output of receiver ensures limitation on maximum, which, as practice has shown, is also advisable.

It is necessary to note the special value in a shadow flaw detector of a receiver with limitation on minimum and on maximum. Only with such a receiver can sufficient precision of readings be ensured. The schemes used by Kruse and N. F. Otpushchennikov, which measured the amplitude of oscillations passing through metal with a vacuum-tube voltmeter, do not permit exact judgment about presence of defect, since change of beam intensity is determined by a great number of factors besides the presence of defect zones. As is known, amplitude of oscillations passing through metal in different points is unequal. If it is measured by vacuum-tube voltmeter, obtained values can be depicted by curve a in Fig. 106. If the receiver possess a linear response curve, the indicator switched in on output of it will work in accordance with curve a, and decipering its reading will be difficult. If the receiver has amplitude selection,

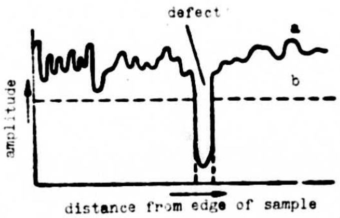

Fig. 106. Amplitude of oscillations passing through metallic sample under control by shadow method.

its work will be depicted by line b on the same Fig. 106. It is absolutely obvious that the indicator readings will be more distinct. At ideal amplitude response curve of receiver with noise cutoff, oscillations whose amplitude is below certain critical value $U_{кр}$, are not passed by the receiver since the receiver is locked against these oscillations. Starting with $U_{кр}$ the receiver is unlocked and all oscillations given on output identical value $U_{вых}$. $U_{кр}$ may be changed, changing thereby threshold of operation of device, and consequently also sensitivity. Position of line b in Fig. 106 will be changed (line shifts along vertical).

Thus, the indicator (independently of oscillations of amplitude of UZK passing through metal not connected with presence of defect) gives constant readings for that moment when due to presences of defect amplitude will fall below and indicator $U_{кр}$ will show full absence of signal.

Amplitude selection is applied now in all contemporary shadow and also pulse-echo flaw detectors.

Application of amplitude selection of signals considerably increases precision of readings of the flaw detector; however, in the control of articles of even the most simple (plane-parallel) form there can appear additional phenomena preventing UZK from passing. This is not connected with presence of defect and distorts readings of indicator of flaw detector. Such phenomena include interference of UZK, leading to appearance of standing waves (during continuous radiation). A purely standing wave and consequently full impassability of UZK can appear in thin sections; in thicker sections, due to more noticeable difference of amplitudes of incident and reflected waves, on the standing wave is superimposed a traveling wave (standing-wave ratio decreases) and passage of UZK becomes noticeable.

Complete removal of the influence of standing waves is possible only by the application of frequency modulation of UZK.

In this case through any section of the article will pass waves of different length, and if a given section for a wave of defined lengtn standing waves are formed, waves of other length will pass freely.

Conditions of maximum and minimum transmittance of plate of assigned thickness d, immersed in another medium can be expressed in the following way:

maximum transmittance

$$d = 2n\frac{\lambda}{4} = \frac{n\lambda}{2}, \text{ or } \frac{d}{2n} = \frac{c}{4f_0}$$

minimum transmittance

$$d = (2 \pm 1)\frac{\lambda}{4}, \text{ or } \frac{d}{2n \pm 1} = \frac{c}{4f_1},$$

where λ_0 and λ_1 – wavelengths; f_0 and f_1 – corresponding frequency of oscillations; c – rate of propagation of oscillations in given medium; n – integer.

Values of c and d are determined by material and dimensions of article, therefore for transition from minimum transmittance to maximum it is necessary to change frequency. Minimum change of frequency sufficient for maximum transmittance can be determined from the relation

$$f_0/f_1 = 2n/2n \pm 1.$$

For resounding articles of considerable thickness besides the fact that interference due to presence of traveling wave has less effect, removal of standing waves is facilitated still because when d increases n is increased, and consequently magnitude of necessary change of frequency decreases. The same occurs and during work on higher frequencies since in this case n also is increased.

Let us define magnitude of necessary change (deviation) of UZK frequency for full removal of influence of standing waves during resounding of article of variable section.

Let us assume that working frequency f_0 = 2.5 MHz, minimum thickness of article d = 5 mm, and rate of propagation of UZK in metal c = $6.2 \cdot 10^6$ mm/s.

Length of elastic wave in metal

$$\lambda_0 = \frac{c}{f_0} = \frac{6{,}2 \cdot 10^6}{2{,}5 \cdot 10^6} = 2{,}5 \text{ мм.}$$

From condition of maximum transmittance we have: $n = \frac{2d}{\lambda_0} = \frac{10}{2.5} = 4$, whence $f_0 : f_1 = 8:9 = 0.89$.

Deviation of frequency necessary to guarantee maximum transmittance will be consequently, Δf = 11%.

It is not difficult to show that when frequency is increased twice, i.e., f_0 = 5 MHz and other equal conditions necessary, deviation of frequency decreases to 6%, and if minimum thickness of article is 15 mm, at 2.5 MHz necessary deviation will be 4%, and at 5 MHz — only 2%. On the other hand, if working frequency is 1.25 MHz, when article is 5 mm thick the required deviation of frequency should be increased to 20%.

Thus, for a large number of cases required deviation of frequency is very small; therefore creation of generators of frequency-modulated oscillations, and even more so, receivers for reception and amplification of these oscillations, is not complicated. Piezoelectric converters, radiating and taking UZK, constitute oscillatory systems with a low quality and possess fully sufficient bandwidth of of transmission for work with frequency-modulated oscillations.

Frequency modulation of oscillations is used at present in shadow flaw detectors, for instance in an instrument of the Lehfeld firm (FRG) in a Morris, Goodyear instrument (USA), and others

Development of pulse technology in recent years permitted removing influence of standing waves by means of transition to pulse conditions. During control of articles of sufficient thickness, pulse conditions ensures absence of interference, inasmuch as the reflected pulse usually does not meet the radiated pulse. However, if thickness of controlled article is small (thin sheet), radiation of pulse cannot be completed by the time reflection occurs and interference can be observed.

In certain contemporary flaw detectors working in pulse conditions modulation of frequency in pulse is used, which improves exploitational characteristics of flaw detector.

It is necessary to say that a pulse regime essentially improves conditions of control of metals possessing a high level of structural reverberation. Beams repeatedly reflected by crystals travel in the controlled article a significantly greater path than the primary beam, and therefore reaches receiver with large retardation in time. If UZK are sent in the form of short pulses, reverberational

noises will reach the UZK receiver after the pulse from the primary beam. If indicator of flaw detector permits time selection of signals, i.e., allows seperate recording signals taken in different time (this is possible in an electron-beam tube), removal of interferences on the part of reverberational noises is considerably facilitated.

Use of pulse radiation against interferences of reverberational character during control by shadow method was first proposed by S. Ya. Sokolov in 1934[1] [126].

Pulse radiation in the shadow method also gives an essential advantage in the sense of removing electrical interferences induced by generator on the receiving-amplifying channel. Under pulse regime at the time of reception and amplification of electrical pulse the generator does not radiate and does not create interferences, which facilitates shielding the receiver-amplifier. Besides during propagation of short pulses interference phenomena are considerably weakened, which leads to decrease of fluctuations of sound pressure in zone of sound shadow, i.e., to "levelling" structure of field in this zone as compared to structure of field observed during propagation of continuous oscillations.

Besides interference resounding is also hindered by considerable refraction of UZK, obtained when the ultrasonic beam from the immersion medium does not fall along the normal to surface of article.

When angle of fall α, determined from relationship $\alpha = 1/n$, where n — refractive index (for real conditions of control of metallic articles in water this angle is near 16°) there is observed total internal reflection of longitudinal oscillations; only shear oscillations enter metal. At further increase of angle of incidence of beam approximately to 27° also total internal reflection and shear oscillations can be observed. In this case UZK will not enter metal at all. Refraction, just as interference of UZK, can lead to incorrect readings, noting nonpassage of UZK in the absence of defects on their path.

From what was said one may see that introduction of UZK normally to surface of article has large value. For this piezoelectric plates should be checked as to symmetry of diagram of directivity, and construction of holder of piezoconverter should provide corresponding adjustment.

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[1]S. Ya. Sokolov. Author's certificate, USSR No. 48894, 1934.

This improves conditions of resounding for articles of flat-parallel form; however, control of articles of more complicated form is not solved by this one measure.

Conditions of passing UZK through an article bounded on one side by a plane and on the other by a curved surface is considerably more complicated, since a beam, even if it is introduced on the part of the flat surface normally to it, is refracted at output through opposite surface of article and does not reach the receiving piezoelectric element.

For control of such articles, having sufficiently clean treated surface, the author [105] developed a self-adjusting receiving head mounted on a corrugated brass nozzle ("bellows").

However, for control of articles bounded on both sides by curved surfaces, a pressed hinged head cannot be used, since due to refraction of beam as soon as it enters the lens, its place of exit shifts from the line on which piezoelectric plates are located.

The author successfully tested and recommended [104] a method allowing resounding of articles of complicated form without considerable refraction of beams. It consists in selection of an intermediate medium in which rate of propagation of UZK equals their rate in the investigated article. In this case beams incident on surface of article not along normal should not undergo refraction.

Unfortunately, absence of liquids in which rate of propagation of UZK would be close to 5000-6000 m/s, for the present excludes use of this method for control of metallic articles. Control of articles from materials in which speed of propagation of UZK is close their speed in water is possible.

Use of this method permitted in 1951-1960 acceptance of the shadow method in the United States, England, FRG and the USSR [134-136] for control of rubber covers; thanks to equality of speeds of propagation of UZK in water and in rubber no refraction of UZK on contour of protector is observed.

A completelty different principle[1] is the basis of the method of compensation developed by the author [105] for resounding articles of complicated form. The method is based on artifical straightening the path of a refracted beam by means

[1]D. S. Shrayber. Author's certificate, No. 59686, USSR 1939.

of additional refraction in the opposite direction by special compensators. For instance, for an article having the form of a double convex lens it is necessary to have on every side a gathering ultrasonic beams, inasmuch as the actual lens disperses them. Such a compensator can be a flat-concave line of the same curvature. A diagram of resounding with compensators is shown in Fig. 107. The gap to be filled with water between article I and compensators II and III should be very small (d ≈ 0.5 mm). Under this condition beams passing through the system are not displaced and a system analogous to that known in optics as a "direct view prism" is obtained.

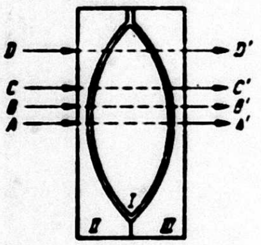
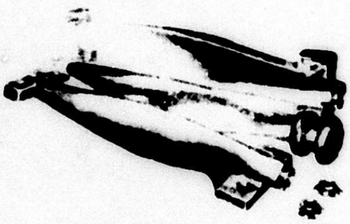


Fig. 107. Diagram of resounding lens with compensators: I – lens; II, III – compensators. AA', BB' – CC', DD' – beams.

Conditions of passage of UZK through a body of asymmetric form are somewhat worsened – displacement of beam is observed limiting value of which, however, cannot exceed 2d.

Application of compensators permitted resounding of article of such complicated form as a propeller blade stamped from duralumin.

For resounding the blade two compensators were made from duralumin. The gap was calculated, taking into account permissible fluctuations of thickness of blade, and on the average was 1 mm. Blade and components of compensators are shown in Fig. 108, the complete system – in Fig. 109.



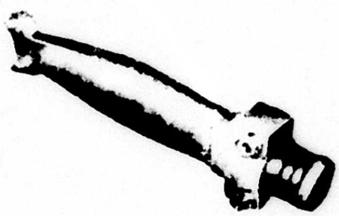


Fig. 108. Blade with compensators from duralumin.

Fig. 109. Propeller blade of aircraft engine readied for resounding with compensators.

For reliable control ensuring detection of defects whose dimensions exceed a certain assigned value, a correct system of scanning the controlled article by ultrasonic beam should be selected.

Articles of flat-parallel form or those which obtained this form as a result of using compensators are conveniently scanned by lines with a defined step depending on minimum dimensions of defects subject to detection.

For line scanning smooth forward-backward motion of article or beam is required and step displacement of it by the magnitude of a step upon completion of a line (Fig. 110a). If dimensions of article are small, sometimes it is advisable to move it relative to the ultrasonic beam during resounding. During work with long articles a more compact installation will be obtained if the article is secured motionlessly and the ultrasonic beam is moved.

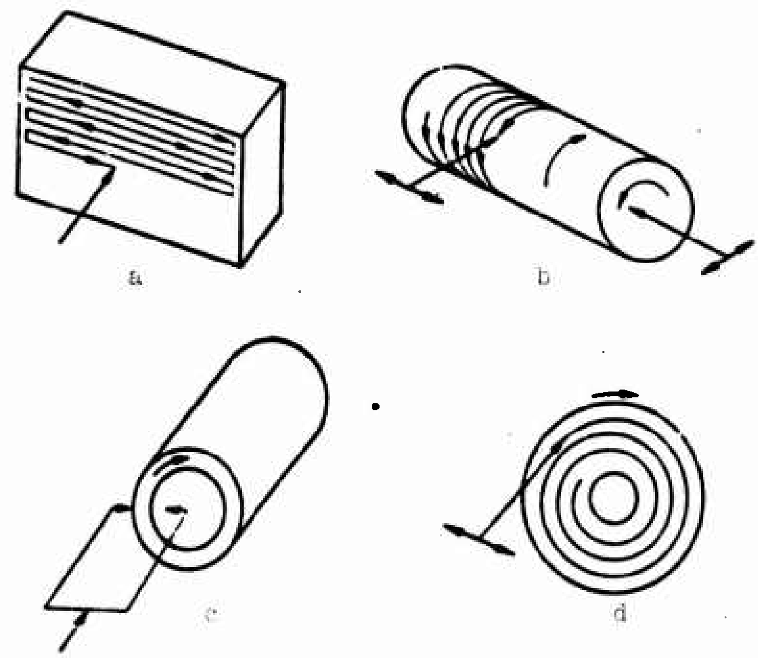


Fig. 110. Diagram of scanning articles of different form: a) body bounded by parallel planes; b) solid cylinder; c) hollow cylinder; d) flat disk.

For articles having the form of bodies of revolution (shafts, cylinders) scanning is more expediently done along a helix: for this the article revolves around a longitudinal axis and the beam is moved along the generatrix. Radiator and receiver of UZK are rigidly secured along diameter of body of revolution (Fig. 110b). If the article is hollow (pipe) it is advisable to place the UZK radiator inside the pipe and the receiver on the outside, orienting them along the radius (Fig. 110c).

Finally, if the article has the form of a flat disk, scanning is carried out along a flat spiral — disk revolves around axis and beam is moved along radius of disk (Fig. 110d).

Continuous scanning is easily carried out when acoustic contact is immersed. In this case cleanness of treatment of surface of controlled article does not essentially influence constancy of contact; it must be considered only for selection of frequency of UZK: the more rough the treatment the lower the frequency should be (and the lower the sensitivity obtained).

In the first flaw detectors of S. Ya. Sokolov the immersion liquid for improvement of electrical insulation was transformer oil. Kruse, wishing to increase senitivity by decreasing losses on reflection during transition of UZK through the immersion liquid - metal boundary used mercury for this. This variant, however, should be recognized as absolutely unfit for industrial conditions since mercury is poisonous and renders destructive action on certain metals.

Inasmuch as immersion contact cannot always be realized the introduction of UZK through a film of liquid is also used. In this case a decisive role is played by cleanness of surface treatment of article. If surface of article is uneven the acoustic contact is inconstant and readings are unstable. A certain way from such a position is the use of piezoelectric converters with rubber or plastic (teflon) caps; such caps, pressed to surface of article allow reliable acoustic contact (Fig. 111). It is clear, however, that continuous scanning when there is considerable roughness of the surface is hampered the piezoelectric converters must move by means of "walking" from point to point.

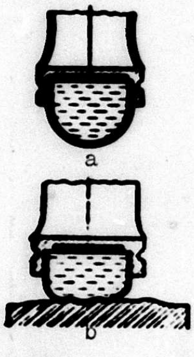


Fig. 111. Searching head with rubber cap for controlling articles with rough surface: a) structural diagram of head; b) contact with rough surface.

In certain cases when it is difficult to carry out immersion contact due to large dimensions of article, and contact through film of liquid due to insufficient cleanness of surface treatment, it is possible to use the jet contact (Fig. 112) proposed by Trost [138]. However, one should consider that turbulance of stream, leading to formation of air bubbles, may cause instability of acoustic contact, therefore such a method may be used only with great caution.

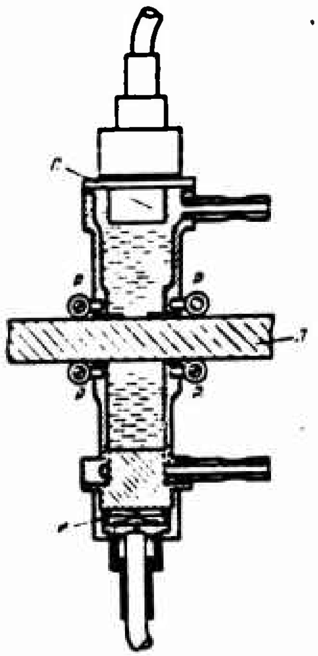


Fig. 112. Trost searching heads with jet contact, intended for control of sheets and plates: Л – controlled sheets; И – radiating; П – receiving head; Р – rollers.

For more clear determination of contours of revealed defect, it is advisable to use a small receiver or to diaphragm the UZK receiver.

Efficiency of control during line scanning, in general very low, can be in certain cases increased by application of several pairs of UZK radiators and receivers fastened to a special support and in turn switched in with a high-speed commutator. Such a system is used, for instance, in the below-described "Zonemeter." The original setup for a high-speed commutator was developed by G. V. Prorokov [139]. A highly efficient multichannel device for the control of steel sheets against stratification, using a special commutation circuit of a very large (near 300 pair) number of UZK radiators and receivers was described by L. G. Merkulov and others [140]. As will be shown below, however, highly productive control of sheet material at present can be carried out by an improved method.

There is essential value, especially in conditions of industrial control, in the system of reading and recording readings of a flaw detector. Recording is necessary where an objective document indicating results of control is needed.

Readings of UZK passing through the controlled article can be carried out by different methods: observation of relief ("ripple") on surface of liquid bath, measurement of intensity of beam by pointer-type device, or with an electron-beam tube by means of sound or light indicators, and finally by means of visualization of structure of wave field for UZK receiver.

Recording the readings of a flaw detector can be carried out by different ways. It can be done on light sensitive, or, which is more convenient and fast, on electrothermal paper.

Figure 113 gives the phonogram of blade from duralumin [116] on light sensitive paper using compensators of frequency modulation of UZK and noise cutoff, line scanning, immersion contact and disphragming of the receiving searching head.

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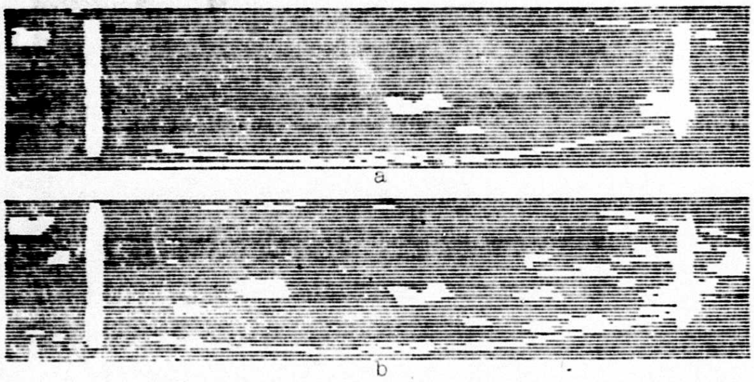

Fig. 113. Phonogram of blade resounded using compensators with frequency modulation a, and without frequency modulation b.

On the phonogram contours of the blade slightly stand out etalons of sensitivity distinctly are reproduced – plates from plywood fastened on right and left part of blade – and defective zones in which after cutting of blade stratifications were revealed are outlines. For comparison is given the phonogram of blade obtained with modulation of frequency of UZK: on it one may see a considerable number of zones where UZK have not passed through which is not connected with presence of defects.

3. Contemporary State and Prospects of Development of Shadow Method

The widest use of the shadow method is in the FRG, Belgium, and partially in France. In the United States, England, and Japan this method of controlling metallic articles is less used. In the USSR the shadow method successfully is used mainly for controlling quality of sheet rolling, bearings, multilayer disks, cable jackets, rubber articles, special plastics and concrete.

Let us note that for control by the shadow method echo of law detectors manufactured in the USSR and abroad can be used. At that time in a number of cases development of specialized equipment is required.

Of original developments in the FRG one should cite the method of Götz [141], allowing control of metallic sheets and plates against the presence of stratifications. In this method ultrasonic oscillations are introduced in metal through liquid medium at an angle different from normal to surface of sheet.

This angle is chosen from calculation of coincidence of speed of advance of track of incident wave along sheet with speed of propagation of bend waves in it. Maximum acoustic transmittance of sheet is observed if there are no defects in it. During scanning of article stratification is revealed by loss of transmittance[1]. At 200-474 kHz such a method can reveal stratification near 30 mm in diameter in plates up to 25 mm thick. Although such sensitivity can in no way be called high, this method is used by Borsig and AEG.

Trost applied searching heads of original construction for control of sheets and plates in which jet acoustic contact is made by means of continuous supply of water into housing of searching head between plate of piezoelectric converter and surface of controlled article. Here necessity of dipping the article in a bath is eliminated. Trost heads are mounted coaxially on hard rods and can shift along surface of article. Water is poured through gap between head and surface of article.

Trost used UZK at frequency 1 MHz with frequency modulation and revealed stratification from 5 mm in diameter in sheets, plates, and profiles.

Ultrasonic flaw detectors designed for controlling articles of simple form are manufactured in the FRG by several firms [142]. The most wide-spread industrial flaw detector type is the "Zonemeter" made by Lehfeldt (Fig. 114)[2]. This instrument works at frequencies of 0.1; 2.85 and 8.5 MHz with frequency modulation. Deviation of frequency accordingly is 5, 130, and 200 kHz; frequency of modulation is 50 Hz. Searching heads of flaw detector are mounted on a support. Heads are supplied with a great number of changeable steel tips designed for control of articles of the most various form. The acoustic contact is brought about by the introduction of a drop of oil between the surface of the controlled article and the tip of the searching head. In the instrument there is smooth adjustment of power of radiated UZK. The receiving device is an h-f amplifier and a dc amplifier on whose outlet is an indicator — millivoltmeter of switch type. In

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[1]It is necessary to note that at the present the method of control of sheet material is very effectively used with waveguide effect and is, in essence, a development of the method of Götz.

[2]Figures 114, 115, 128, 129, 139, 143, 146, 156, 158, 159, 160, 161, 162, 163, 182, 186, 246, 247, 248, 250, 251, 254, 264, 271, 272, 273, 276, 279, are on the insert between pp. 123 and 135.

parallel to the indicator is switched in a relay, which works if readings of the indicator drop to middle of scale. Here there is swtiched in a light or sound signal, indicating detection of defect.

Using tips of searching heads with 3 mm diameter it is possible, with the described flaw detector, to reveal in sheets up to 10 mm thick defects 1 mm in diameter. For the "Zonemeter" special slanted searching heads were developed shaped in the form of an attachment for control of a welded seam cylinder housings, etc.

In the considered flaw detectors scanning is done by single searching heads, which does not permit control with any considerable speed. The problem of increasing productivity of ultrasonic control of radical solution has not yet been obtained and in each specific case any methods of acceleration of control are applied. So, for control of sheet material to the "Zonemeter" is connected a specially developed device consisting of a high speed commutator switching in by turn one of ten pair of searching heads fastened in a special support (Fig. 115). The sheet is resounded simultaneously by ten bands, which considerably accelerates control. However, requirements for cleanness of surface during work with such a "high-speed" method essentially are increased, and the problem of continuous and reliable acoustic contact becomes very serious.

The Belgian firm "Ultrasonel" mastered production of shadow flaw detectors designed for control of different metallic and nonmetallic articles (for instance plates and pipes from bakelite) against internal stratifications [143].

It is necessary to note that the tendency to expansion of the circle of controlled articles from nonmetallic materials has become in recent years especially clear. In particular, in a number of countries automobile and aviation coverings on cracks in rubber and sealing of rubber from fabric are successfully controlled. For instance, setups developed by Morris [134] (USA) and Hatfield [135] (England) are very succesful in controlling coatings. In the latter the radiator is placed inside the covering and sends a divergent beam of UZK at 50 kHz into the body of the covering. On the outside are six receiving heads, each joined with its own receiving head amplifying device, and indicator. Searching heads, as in the Morris setup, can shift, preserving their mutual location, and thus resound all

sections of the covering. Control of cover on the described installation continues several minutos. There is still higher efficiency of the installation created by Lehfeldt and differing by the use of UZK of higher frequency (100 kHz), which increases resolving power (defects with dimensions from 10 mm are detected). Besides, the installation is supplied with ten receiving searching heads and correspondingly has ten amplifiers and indicators. Control is conducted at a speed up to 25 cm/s. Ultrasonic control of rubber covering in recent years has been successfully developed, which promotes exceptionally successful coincidence of the most important physical characteristics of water and rubber for propagation of elastic oscillations. As already was noted, their specific wave impedance are almost identical, which practically ensures absence of reflection of UZK onto the rubber-water boundary. Coincidence of values of speed of UZK in water and in rubber is also very essential: this leads to absence of refraction of UZK onto the rubber-water boundary and permits control of an article of sufficiently complicated form. In particular, if these speeds were not equal, tread ribs on an automobile tire considerably would complicate control due to refraction of UZK.

In the USSR ultrasonic control of articles from nonmetallic materials is also used. Thus, for control of rubber covers the [TsNIITMASh] (ЦНИИТМАШ) developed the [ShD-1] (ШД-1) flaw detector [136]. Control of massive units from plastic turned out to be very effective. On comparatively low frequencies (inasmuch as damping of UZK in plastics is great) high sensitivity can be obtained and the smallest heterogeneities detected. Here the use of a homogeneous isotropic medium (plastic) over a heterogeneous anisotropic (complicated alloy) medium is the influence. In the last case scattering of UZK by structural components of an alloy leads to appearance of interferences and to necessity of lowering sensitivity. In case of controlling a plastic such scattering is not observed. The degree of contrast of a wave field for UZK receiver is sufficiently high and the sensitive indicator reacts to an insignificant decrease of intensity of sound field after a small defect, as a result of which real sensitivity of instrument can attain very high values. Very successful results are obtained on an installation of a similar type, created by D. F. Vasil'yev and N. F. Shustov [144]. This installation constitutes semiautomation working on a frequency near 100 kHz with application of immersion

variant of acoustic contact and scanning along a helix. To produce an objective document indicating results of control in this installation, readings are recorded on photographic paper with a loop oscillograph (Fig. 116). Such a system of recording permits judging as to the presence of defects, but it complicated and has low efficiency.

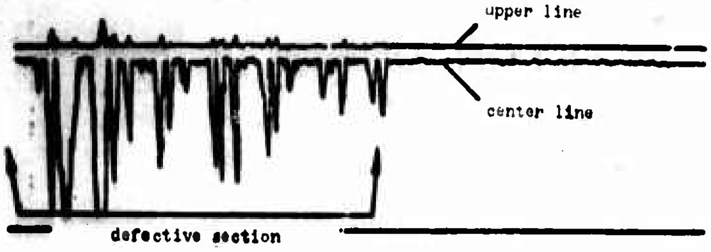


Fig. 116. Sample of recording of readings of a flow detector on oscillograph paper [144].

It is considerably more graphic, more efficient and simpler to record readings of flaw detector [V4-9T] (B4-9T) for control of multilayer disks in which to a steel base by the method of diffusion brazing "are soldered" elements from ceramic metal. In this semiautomatic flaw detector, developed in 1956 by G. V. Prorokov, pulse radiation of UZK at 1 MHz is used, focusing of UZK with a flat-concave lens (i.e., a "point" radiator of UZK is made), immersion of acoustic contact, scanning along a flat spiral and recording of readings on electrothermal paper is carried out. To output of amplifier of flaw detector is connected a writing device consisting of a tungsten point pressed to a sheet of electrothermal paper fastened to a metallic disk. This disk is planted on one axis with the controlled disk, and therefore motion of point with respect to paper accurately corresponds to motion of ultrasonic beam relatively to controlled disk.

If in the disk on the path of the UZK there are no defects, at output of amplifier develops voltage sufficient for formation of spark discharge between tungsten point and metallic disk on which is fastened electrothermal paper. When there are skips in the spark the paper is burned and on its surface appears a clear graphite trace in the form of a spiral, following the scanning pattern.

Presence of defects leads to voltage drop on output of amplifier and to cessation of spark discharge. On the paper in these places the graphite trace is interrupted and in further tracing there appears a white spot in the spiral (Fig. 117) in form and dimensions corresponding to the revealed defect — disturbance of cohesion of cermet element with metallic basis.

Fig. 117. Sample of recording of readings of a flaw detector on electrothermal paper.

Among shadow flaw detectors for control of metallic articles developed in recent years in the USSR we should note several more installations.

A shadow flaw detector for control of large dimension inserts of bearings of diesel locomotives, developed by R. G. Bogatyrev [145] is a semiautomatic installation working in pulse regime with application of immersion acoustic contact and scanning along a helix. The controlled insert is placed in a bath with water on a table revolving around a vertical axis, and a rigidly and coaxially mounted radiator and receiver of UZK oriented with respect to radius of insert and smoothly travelling along the vertical permit resounding through one wall and clear detection of the zone of disturbance of cohesion between antifriction layer and steel base of insert. A distinctive feature of this installation utilized for control of serial production in industrial conditions is the presence of a special device for automatic signalling upon detection of defects.

Flaw detector [UZDR-60] (УЗДР-60), described by B. A. Petrov [146], and used for control of inserts of bearings is a development of this installation. This flaw detector works in pulse conditions on a frequency of 2.5 MHz, is designed for immersion contact or application of contact lubricant. Upon detection of a defect there is an automatic signal.

The UZDR-60 is equipped with special heads allowing control by "mirror" variant of shadow method with separate searching heads. A diagram of such control is given on Fig. 118. UZK sent by radiator at a small angle to the surface of the antifriction layer (bronze, babbit) are slightly refracted as they pass through this surface (refractive index 2-3), then as they pass through the boundary of this layer with steel experience additional insignificant refraction (refractive index 1.5-2), are reflected from external surface of steel insert and return to UZK receiver, located in water a certain distance from the radiator. At good

cohesion of antifriction layer with steel the receiver records passage of UZK pulse. If on the path of beam there are zones of scaling the receiver marks the defect by absence of a pulse. As the UZK radiator and receiver move along the line parallel to the generatrix of the cylindrical surface the defect will be marked twice: at the intersection with incident and reflected beam.

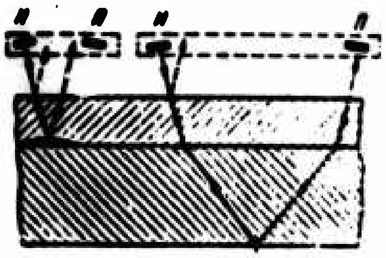


Fig. 118. Diagram of control of inserts of bearings by mirror variant of shadow method [146]: И — radiator; П — receiver.

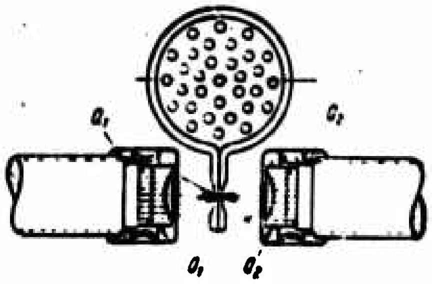


Fig. 119. Diagram of quality control of cold-welded seam [147]. Q_1, Q_2 — piezoelements; 0, 0_2 — lens; K — controlled seam.

The original automatic shadow flaw detector — for quality control of cold-welded seam of aluminum cable sheathing was developed by K. O. Levitskiy [147]. This flaw detector, built into the machine executing cold welding of seam, uses UZK radiator with system of focusing (Fig. 119) and possesses great productivity and sensitivity, making it possible to reveal defects of small dimensions.

The most refined from the point of view of productivity of automation and recording of results of control is the previously mentioned installation for control of rolled steel sheets, developed by L. G. Merkulov, V. M. Verevkin, N. A. Yevdokimov and K. V. Zharkov [140]. In this installation, whose principle of operation is explained by the simplified block-diagram shown in Fig. 120, a special method is used for connecting UZK radiators and receivers in groups, allowing an essential decrease in the number of transmission channels for information when there is a large number of elements of decomposition.

A steel sheet up to 2800 mm wide and 10 + mm thick advances in water between two rulers on which is mounted 288 pair of quartz UZK radiators and receivers, at a speed up to 10 m/min.

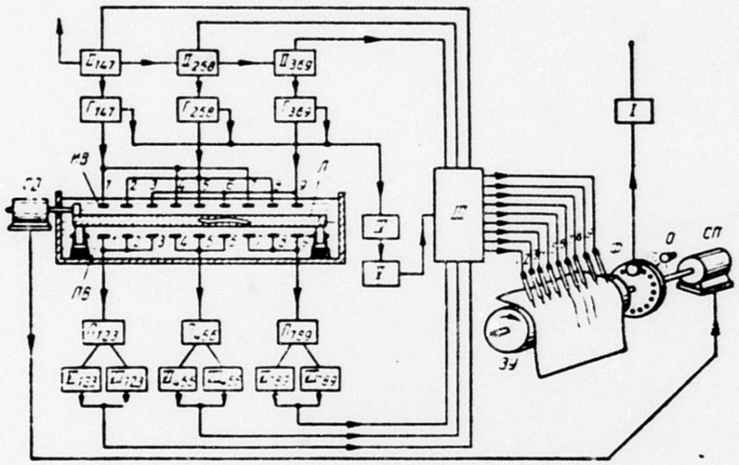


Fig. 120. Block-diagram of installation for control of steel sheets [140]: Л — controlled sheet; ИВ, ПВ — radiating and receiving vibrators; СД, СП — controlling selsyn; О — illuminator; Ф — photoresistor; ЗУ — recording device; I — amplifier-limiter; II, VI, VII — Kipp relay; III — resolver; Г — pulse generators; IV — delay block; V — power amplifier; П — receivers. Figures — number of channels.

When there is stratification in the sheet the UZK receivers fix a sound shadow, and the corresponding needle of the recording arrangement traces a dark line on electrothermal paper. As a result of this paper it is possible to see contours of resounded sheet and outlines of internal defects (Fig. 121).

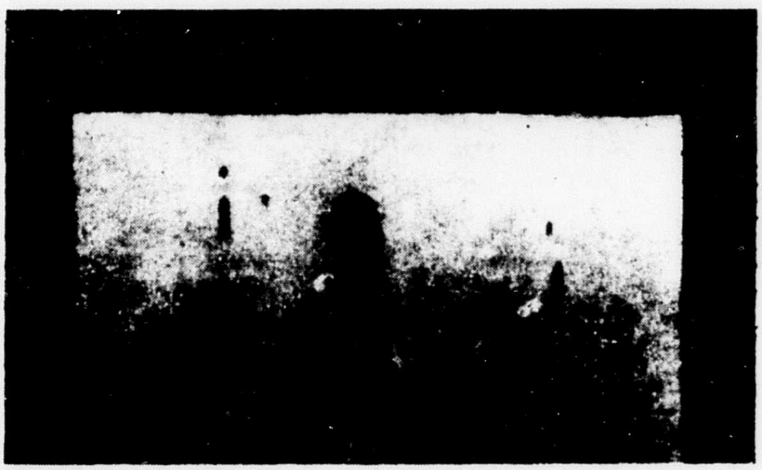


Fig. 121. Sample of recording of statification in steel sheet 2300 mm wide and 40 mm thick [140].

In France [148] the shadow method is used for partial solution of a very urgent problem — quality control of a metal — metal bond. In separate cases sufficiently good effect is obtained.

All the above instruments work using longitudinal ultrasonic waves. Essentially the use of normal waves gives new possibilities for the shadow method. The shadow method with application of normal waves is used at present mainly for control of sheet material pipes, and wire, where here, just as with the use of longitudinal waves, a tendency to automation of resounding is observed [149, 150].

Normal waves are connected with waveguide mechanism of UZK propagation. They can exist only in sheets and shells (for instance in the wall of a pipe) of comparatively small thickness. For excitation of normal waves usually longitudinal oscillations are used, incident on the surface of the controlled article at an angle different from zero. Between angle of incidence, thickness of sheet, and elastic properties of material there exists a connection which makes it possible to find defined discrete angles of incidence corresponding to defined forms and orders of normal waves. The graph shown in Fig. 122 shows that, for instance, at frequency f = 2.85 MHz in a steel plate 1 mm thick it is possible to excite symmetrical normal wave of zero order (curve S_0), if longitudinal UZK fall at 45°, or an antisymmetrical normal wave of the first order (curve a_1) when longitudinal UZK fall at 22.5°. Introduction of UZK into platinum can be carried out either by the immersion method or through a layer of lubricant.

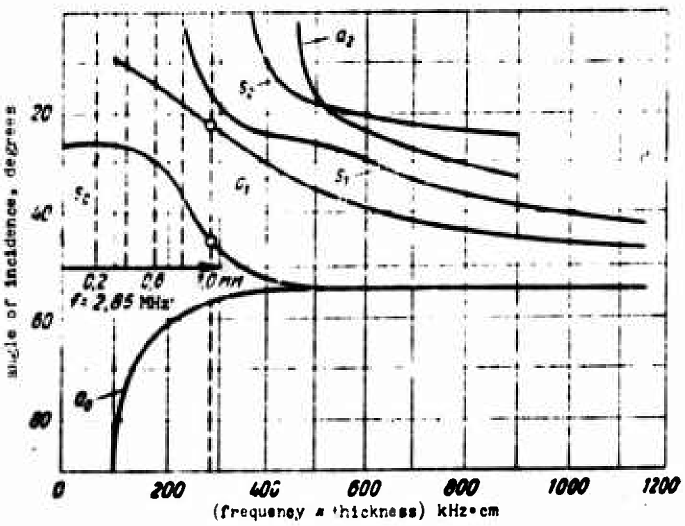


Fig. 122. Graph for determination of conditions of control using normal waves [129]: a — antisymmetrical waves, s — symmetrical waves.

A normal wave (symmetrical or antisymmetrical), excited at the point of introduction of longitudinal UZK into a plate, propagates in the plate in the form of directed beam whose axis lies in plane of incidence of longitudinal UZK. If a certain distance from point of excitation to UZK receiver (radiator

and receiver can be located only on one side of the article), longitudinal oscillations radiated by surface of plate at defined angles (reverse transformation of normal waves into longitudinal) will be accepted by it and marked by the indicator.

Waveguide character of propagation of normal waves in a plate, sheet, or wall of pipe, leads to considerable reflection of UZK from different heterogeneities, having the state of a reflecting surfaces or a section of the waveguide, and consequently, to a sharp fall of amplitude of oscillations after these heterogeneities, analogously to what takes place in the zone of sound shade. The reflector, constituting a disturbance of continuity (stratification), oriented parallel to the surface, causes predominant reflection of symmetrical waves. Transverse discontinuities, oriented to perpendicular to surfaces, reflect mainly antisymmetrical waves.

Figure 123 gives an idea about the control setup of a sheet for stratifications using of normal waves. An essential advantage of using normal waves is that after one passage by one pair of heads a rather large zone of the article is controlled. When longitudinal waves are used, if the area of the checked zone is determined only by diameter of head, when normal waves are used the magnitude of this zone depends also on distance between heads. Increase of this distance (which can be brought to tens of centimeters) permits an essential increase of productivity of control.

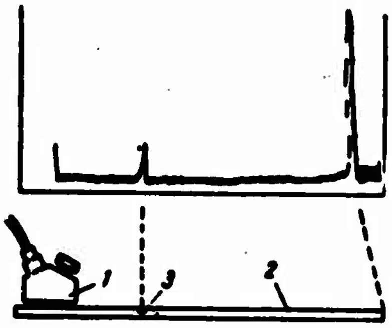
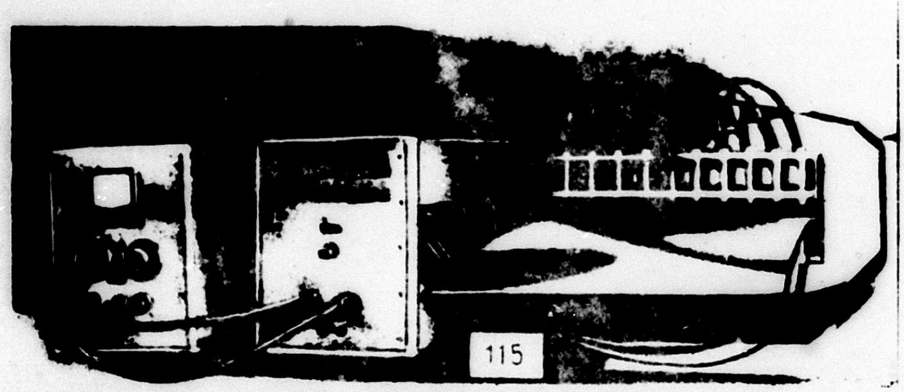
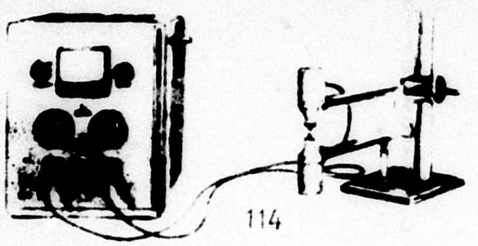


Fig. 123. Diagram of control of sheet for the presence of stratifications using normal waves [80]: 1 — UZK radiator; 2 — UZK sheet; 3 — stratification.

In the FRG very successful installations have been developed for automatic control of sheets and pipes. One of them, designed for control of sheets, is one section of a production line [151]. In it the method of introduction of UZK through a layer of contact lubricant is used. Work is carried out simultaneously by three pairs of heads. The sheet is not completely controlled, but only in the three zones having the form of parallel bands 30 cm wide (distance between radiating and receiving heads of one pair). Distance between bands is 50 cm. Lubricant of contact surface, pressing heads to the sheet, and feeding the sheet





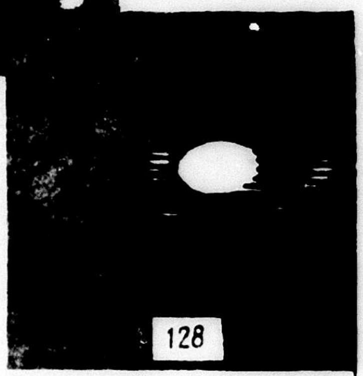
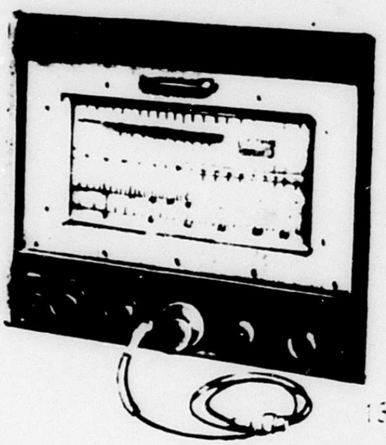


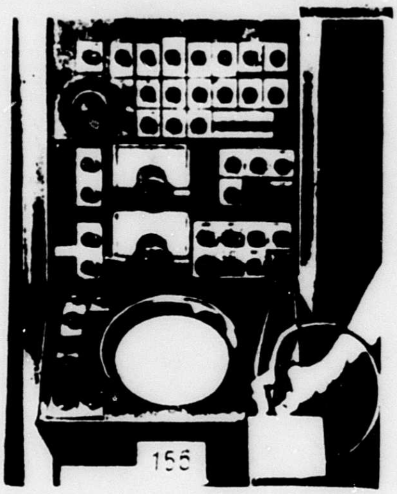
Fig. 114. Zonemeter (Lehfeldt, FRG).

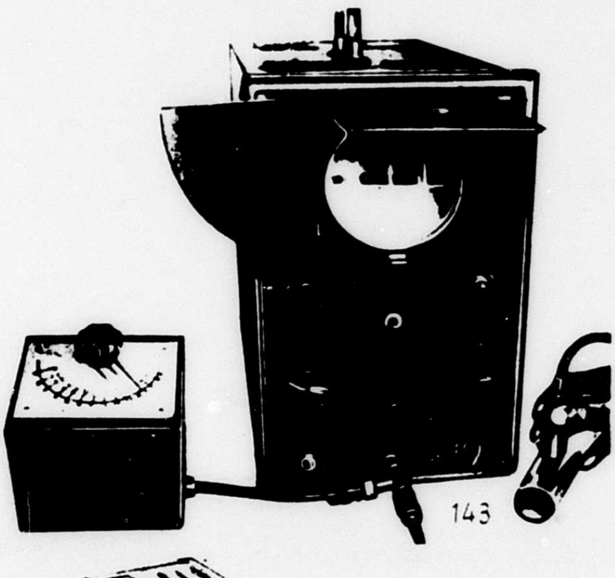
Fig. 115. Attachment to Zonemeter for highly productive control of sheets.

Fig. 128. Specular reflection of elastic oscillations from a sphere, observed on the screen sound-electronic converter [169].

Fig. 129. Image of sound shadow from a flat test object, observed on screen sound-electronic converter.







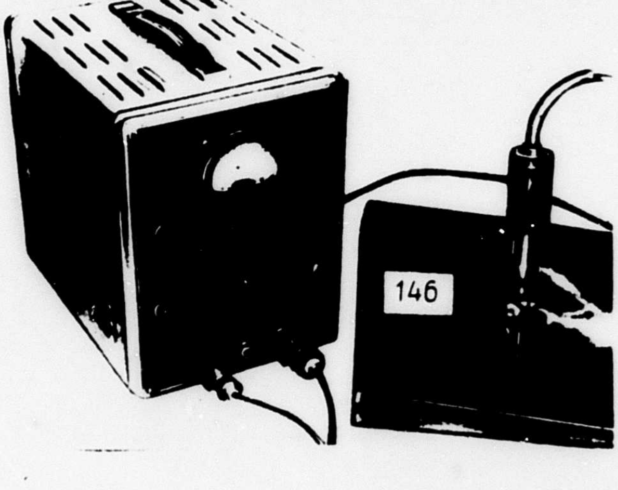
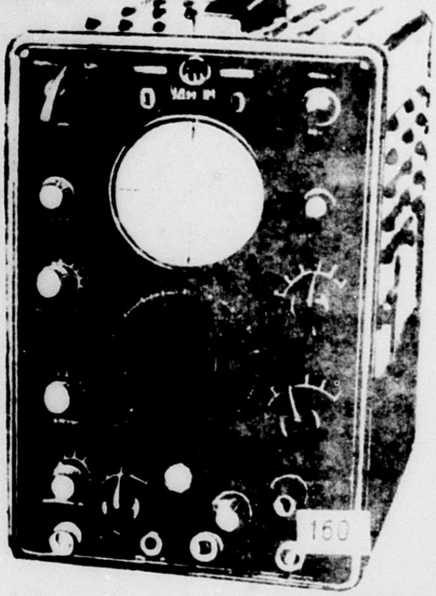


Fig. 139. Vidigage-type ultrasonic resonance flaw detector – thickness gauge (Branson).

Fig. 143. Overall view of flaw detector-thickness V4-8R gauge with attachment (reading device with measuring circuits).

Fig. 146. Quality control of bonding using the IAD-2 [190].

Fig. 156. First industrial pulse-echo flaw detector (Reflectoscope, USA, Sperry).



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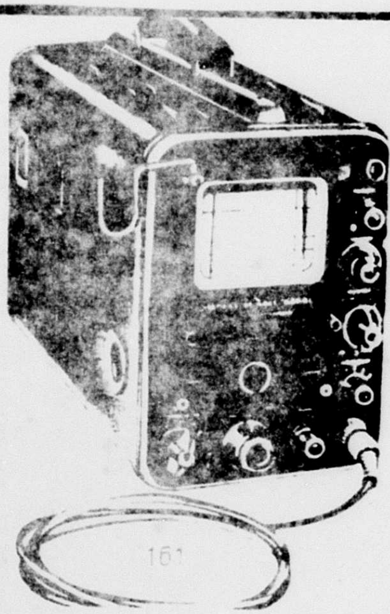

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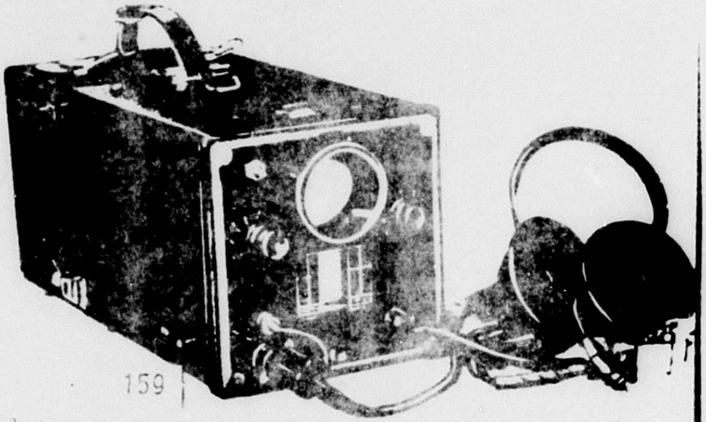

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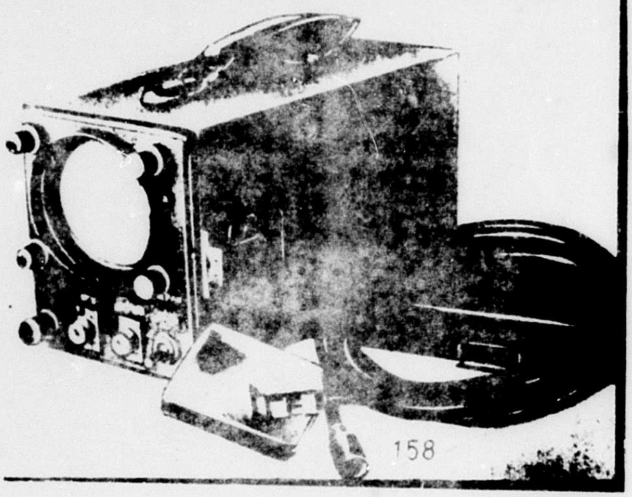

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Fig. 158. Pulse-echo flaw detector UZDL-61 for control of blades.

Fig. 159. Pulse-echo flaw detector UZD-NIIM-5 (NII bridges).

Fig. 160. Pulse-echo flaw detector UDM-1M Precision Electrical Instruments Plant.

Fig. 161. Pulse-echo flaw detector USJP-10 (FRG, Krautkrämer).

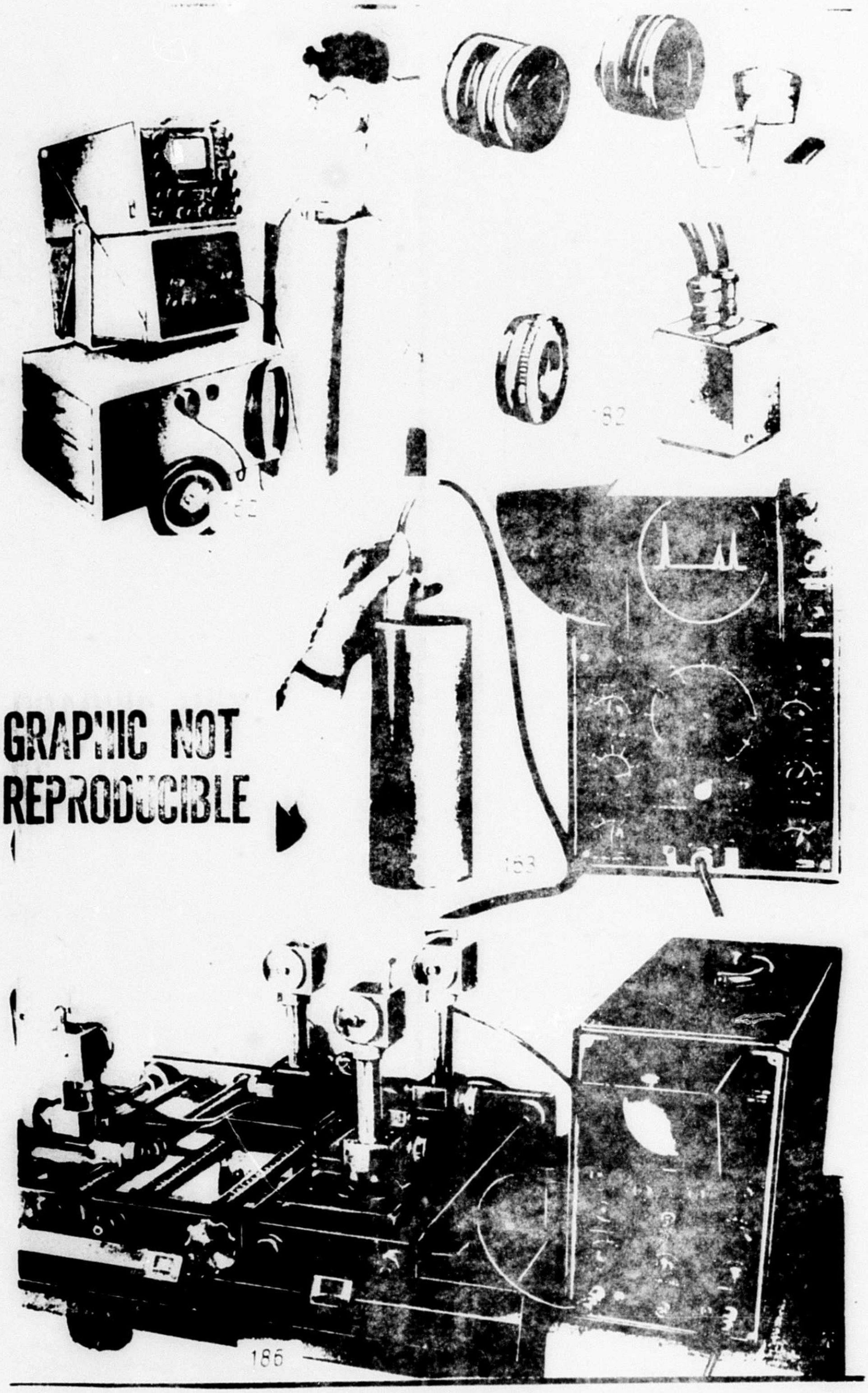
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Fig. 162. Pulse-echo flaw detector "Mark VI" (England, Kelvin and Hughes).

Fig. 163. Pulse-echo flaw detector V4-7I.

Fig. 182. Separately combined searching head (Kelvin and Hughes).

Fig. 186. Installation for investigation of characteristics of methods of ultrasonic defectoscopy by means of simulation in water.

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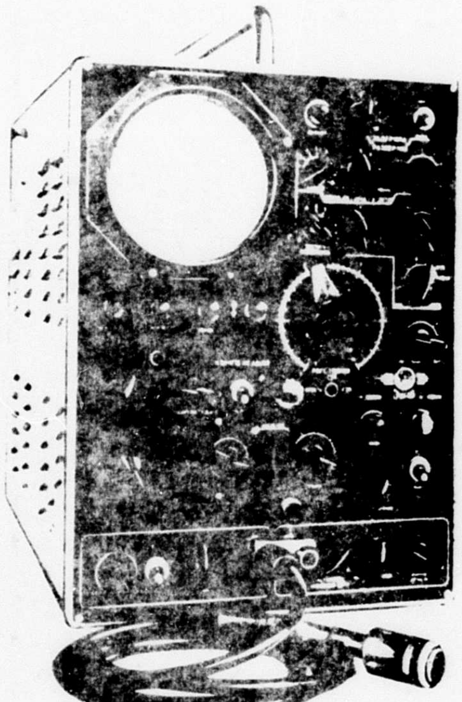

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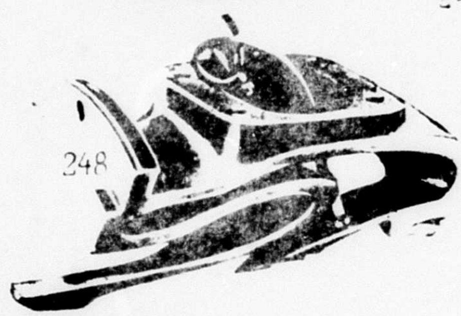
Fig. 246. Overall view of echo flaw detector DUK-6V.

Fig. 247. Overall view of echo flaw detector DUK-5V.

Fig. 248. Measurement of thickness of wall in cast-iron poured component of solid form with the help of a special head [94].



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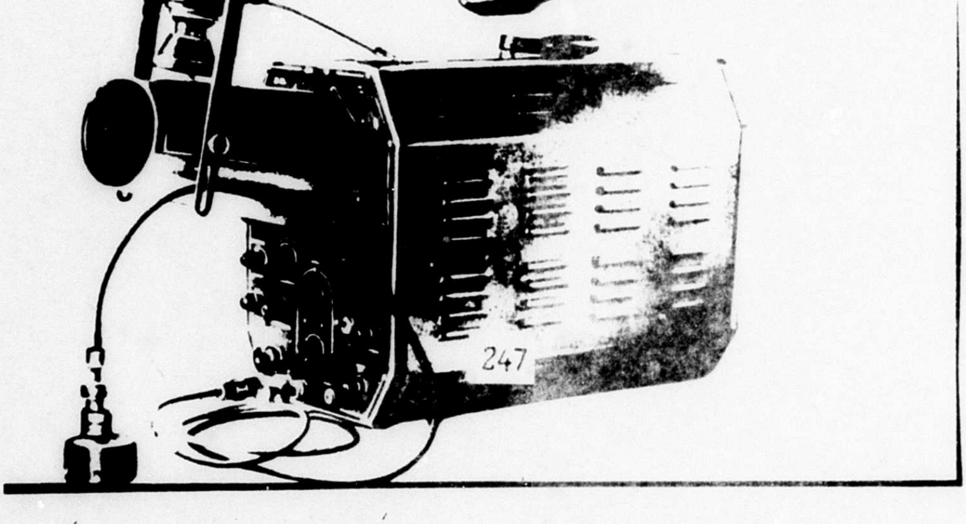

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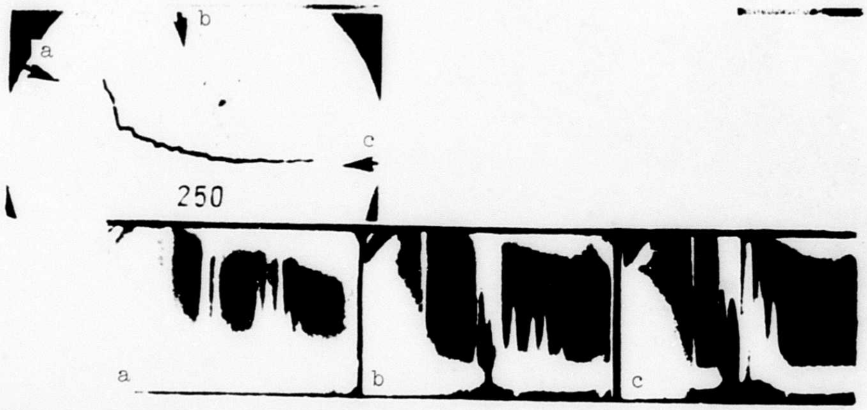


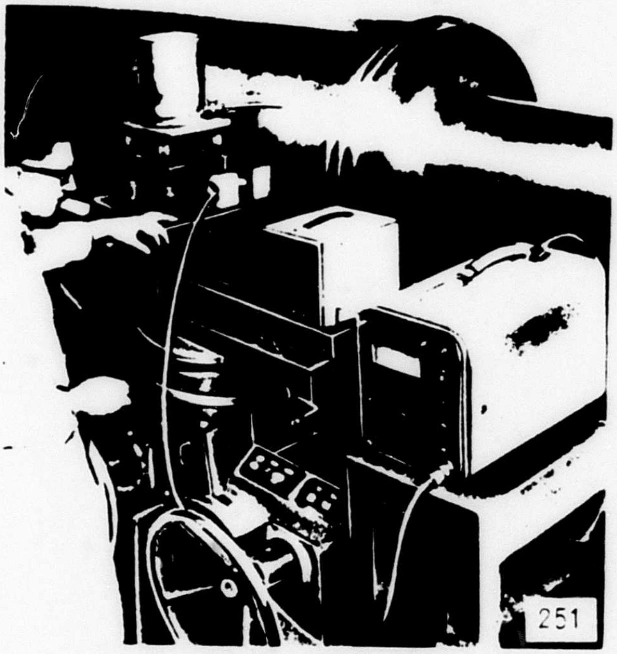
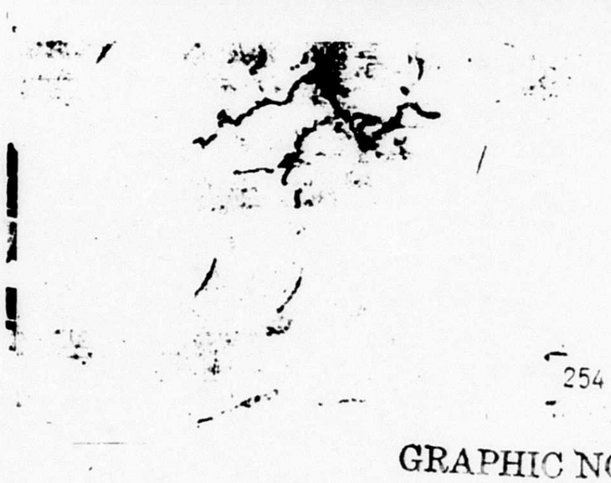


Fig. 250. Internal crack in a large scale ingot from an aluminum alloy (A. P. Saltykov): a, b, c — directions of resounding, and the corresponded pictures are observed on the instrument screen.

Fig. 251. Control of blank of rotor of turbogenerator by contact echo — method [94].

Fig. 254. Overall view of installation for control of profiles by the echo method in an immersion variant.



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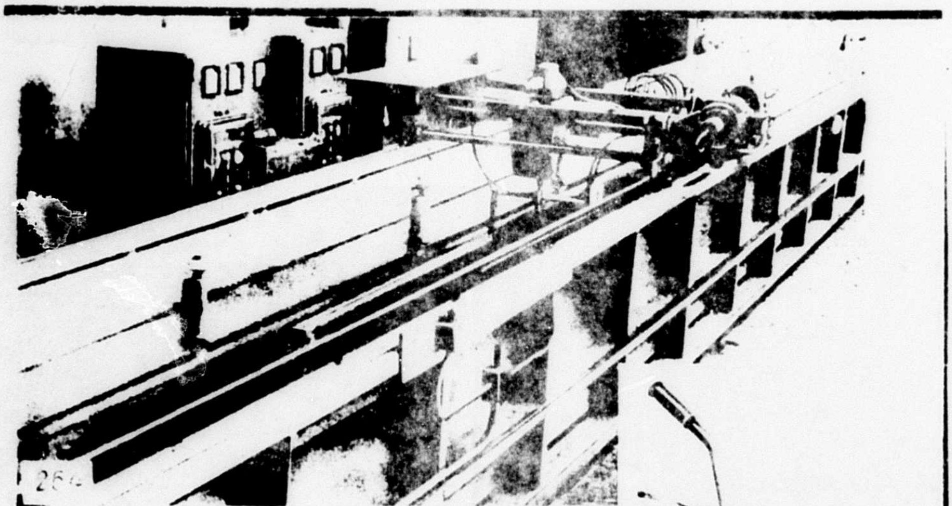

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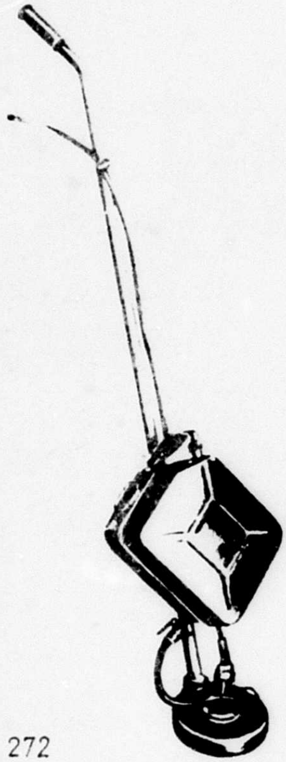

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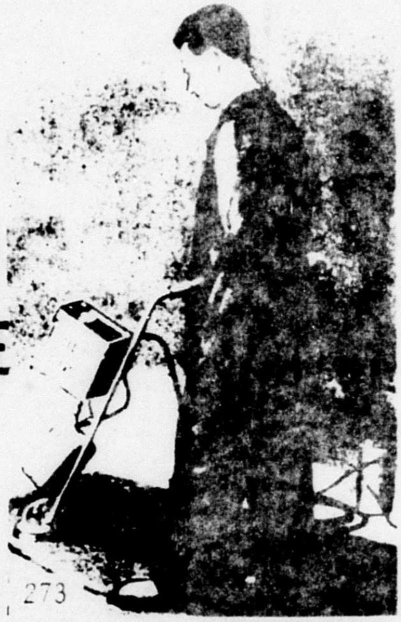

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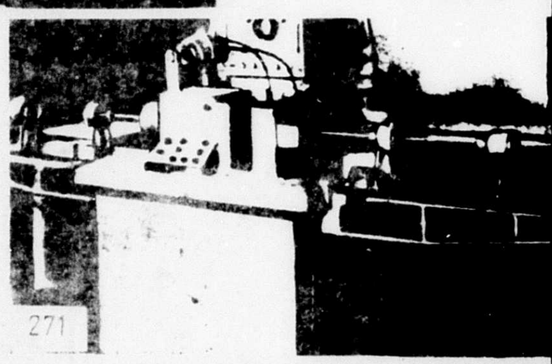

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Fig. 264. Overall view of installation for control of profiles by the echo method in an immersion variant.

Fig. 271. The IDTs-3M for automated control of pipes.

Fig. 272. Searching head with jet contact for control of rolled plates (Krautkrämer).

Fig. 273. Control of rolled plate using a searching head with jet contact. On handle of head is a tank for contact lubricant and also a small echo flaw detector (Krautkrämer).

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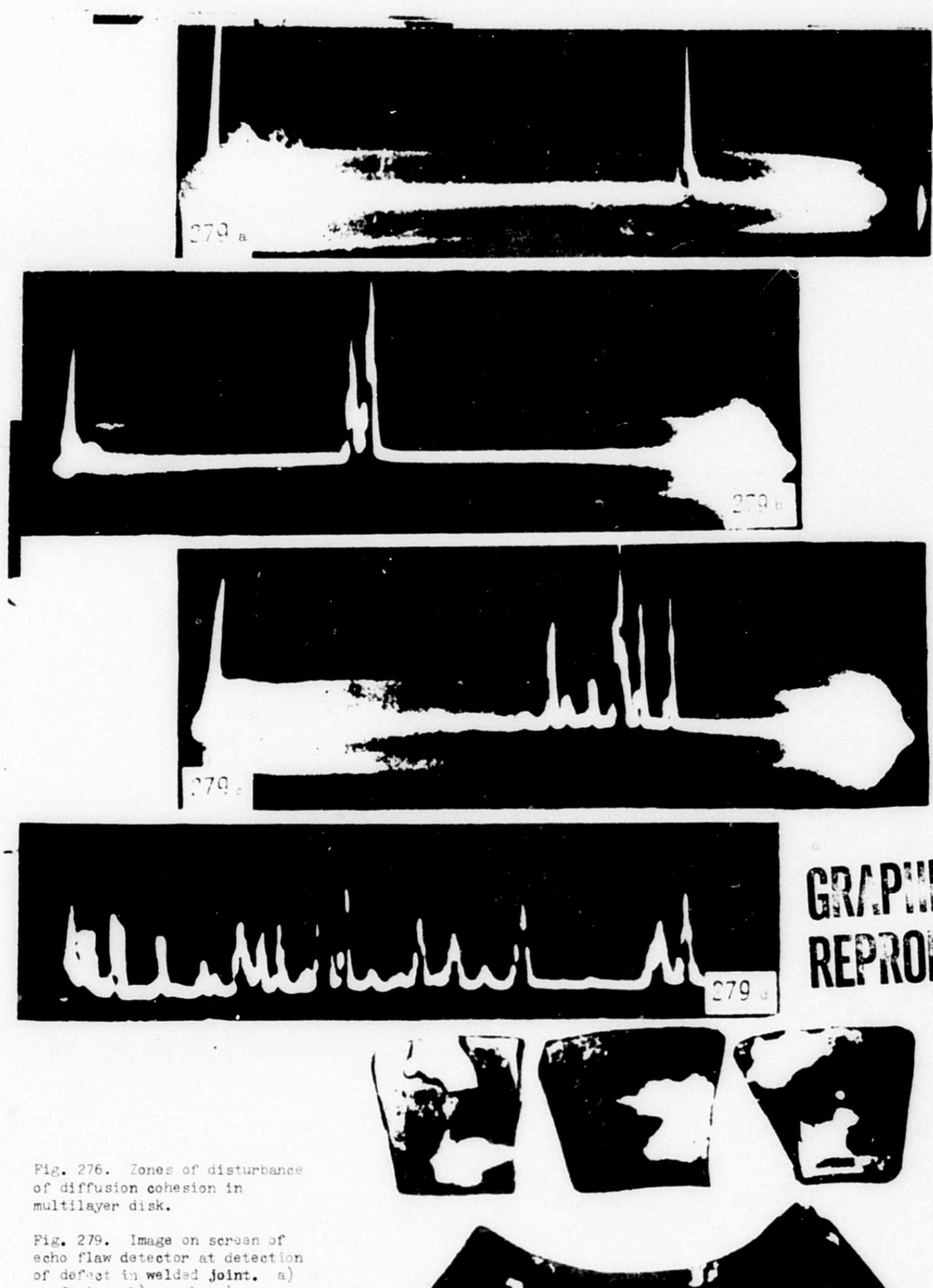

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Fig. 276. Zones of disturbance of diffusion cohesion in multilayer disk.

Fig. 279. Image on screen of echo flaw detector at detection of defect in welded joint. a) nonfusion, b) crack, c) group of cracks, d) porosity (V. A. Tsechal').

at 0.1 to 1 m/s is carried out automatically. The installation is equipped with a special device for signalling the presence of a defect.

An immersion variant of the shadow method using normal waves has been used for the control of pipes [149], sheets [150], and for detection of defects such as disturbance of bonding between an external sheet (or pipe) and the base material [152].

Figure 124 shows the diagram of control of welded pipes by this method. Location of radiating head И is such that longitudinal elastic oscillations fall from a liquid onto the surface of the pipe at an angle ensuring the excitation of normal waves. When the latter propagate in the pipe wall this wall radiates into the liquid longitudinal waves which are trapped by receiving head П. When there is a defect in the controlled section of pipe (in welded seam) the normal wave is reflected from it and its intensity in zone of location of receiving head decreases.

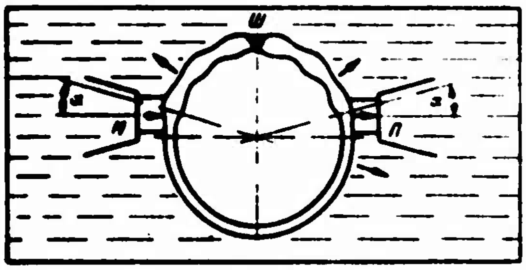

Fig. 124. Diagram of control of welded pipes for defects in the welded seam using normal waves [149]: И – radiator; П – receiver; Ш – seam.

Intensity of longitudinal wave received by the head decreases also. Thus, criterion of presence of defect is decrease of signal on receiving head. Pipes with a wall 0.3-2.5 mm thick are checked on a frequency of 2.0 MHz; at 0.6-6 mm thick, 1.6 MHz is used. Sensitivity of the method is very high. When the pipe moves at 20 cm/s defects 1 mm long are revealed. Locations of defects are marked with paint.

Works on creation of similar installations are successfully being conducted also in the USSR [153, 154].

Control of sheets by the immersion shadow method with the use of normal waves is analogous to the considered case of control of pipes.

A somewhat different method is used for control of bimetalic intermediate products for detection of zones where there is no cohesion between base metal and external sheet or pipe. Figure 125 gives the diagram of quality control of cohesion of plating layer with base metal. Radiating and receiving head are in liquid on one side of the controlled article and are divided by a soundproof

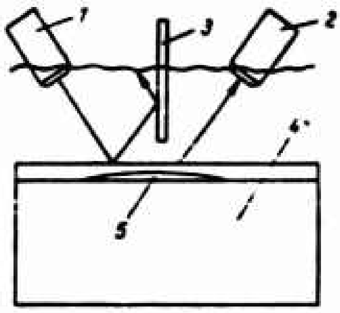

Fig. 125. Diagram of control of fuel elements of atomic reactors (defect — damage of cohesion between aluminum coating and ukranium rod) [152]: 1 — radiator; 2 — receiver; 3 — screen; 4 — rod; 5 — zone of disturbance of cohesion.

screen preventing straight passage of ultrasonic oscillations. If in the article are zones in which the plating layer adheres badly, in the next layer down, as a result of longitudinal ultrasonic oscillations falling on it, there appear normal waves which, propagating along the layer, create a new series of longitudinal waves radiated in the liquid and trapped by receiving head. In case of close cohesion of plating layer with base metal, normal waves are not excited and the receiving head receives no signal. Thus, in distinction from the usual devices for the shadow method, in the given case a defect causes not disappearance but appearance of a signal. A similar method reveals zones of disturbance of cohesion between a thin (1.1 mm) aluminum coating and a uranium rod in fuel elements of atomic reactors [152].

Possibilities of the shadow method, as follows from what has been presented, are sufficiently wide. Further development of the shadow method will provide absolute success in a number of cases for control of different articles in industrial conditions. Basic direction of development of the method is dictated by conditions of contemporary level of production — automation of control and increase of its reliability and objectiveness.

As the above variants of setups and designs of shadow flaw detectors show, the paths for automation of control are specific, and in a number of cases reliable and highly productive automatic flaw detectors have already been created and incorporated in production lines. Increase in reliability and objectiveness of control is connected with creation of methods and devices making it possible to obtain an objective document fixing results of control. This problem is solved on one hand by using different systems of recording, and on the other by the creation of methods and devices for visualization of the wave field which allows direct observation of heterogeneities inside resounded article during control, and thereby more correct determination of form, dimensions, and coordinates of defects.

Various methods of visualization of wave field [155] have a different physical basis and in different degree are useful for application in shadow flaw detectors; however, each of them uses as the basic element the sound-optical converter and the majority uses the acoustic lens.

The first visualization of a wave field was made in 1935 by S. Ya. Sokolov [122], using a relief formed on the free surface of liquid when elastic oscillations fell upon it due to deformation of this surface under action of sound pressure and gravity.

This very primitive method of visualization is characterized by comparatively high sensitivity, corresponding to a UZK intensity of the order of 1000 W/m^2 (or sound pressure in water ~0.5 bar) but does not possess sufficient resolving power. Resolving power is determined by diffractional distribution in field of sound image, and for a system free from aberrations it is determined on the basis of relationships known from optics

$$d = \frac{\lambda}{2n \sin \alpha}, \tag{45}$$

where d — minimum ("resolved") distance between two points at which these points are visible separately; λ — wavelength; α — half of aperture angle of system; n — coefficient of refraction on interface of lens and surrounding medium.

In optical systems where n even with the use of specially selected immersion liquids cannot exceed 1.5-1.6, limiting value of denominator in formula (45) is approximately equal to three, from which it follows that resolving power of an optical system can attain a magnitude of the order of one third of a wavelength.

In acoustical systems the value of n is somewhat larger: for a water-metal system it is four. From this Ye. D. Pigulevskiy [131] makes a conclusion concerning the possibility of increasing resolving power of an acoustical system as compared to optical power. However he does not consider that length of an elastic wave at frequencies used in ultrasonic defectoscopy are three orders greater than the length of a light wave. Therefore, and also due to imperfection of acoustic lenses, for which aberration has not been removed, resolving power of the acoustic system should be not more than for the optical (attaining 0.1-0.2 μ), but many times less, which is completely confirmed by experiments of

Ye. D. Pigulevskiy himself[1].

For production in the acoustic system of a resolving power comparable with the optical system, wavelength should be comparable with wavelength of light, for which frequency of UZK should be increased to values of the order $3 \cdot 10^9$ Hz, which for ultrasonic defectoscopy is still unreal.

From what was said it follows that high quality of image is impossible to obtain in the considered system. Quality still worsens due to use of slanting illumination which is graphically confirmed by the above photography obtained by S. Ya. Sokolov (see Fig. 98).

The system of visualization Spengler was considerably improved [156][2]. In his arrangement a relief will be formed on the surface of liquid poured in a vessel mounted on a damping suspension. Above surface of liquid is a hemispheric screen-reflector illuminated be source of light located with respect to ring in lower part of reflector, and in turn illuminating surface of liquid.

In the center of the reflector is a small hole through which it is possible to observe and to photograph the evenly illuminated surface of the liquid. Upon formation of relief on this surface part of the beam illuminating scatters to the sides, not going in the hole for observation. To increase of sensitivity and increase brightness the surface of the liquid is sprinkled with a thin powder of aluminum bronze and distance from surface of liquid to screen is selected sufficiently large. As a result sensitivity is brought to 500 W/m^2 (which corresponds to sound pressure in water ~0.4 bar), and resolving power also is somewhat increased.

Schuster [158] succeeded in increasing the resolving power of S. Ya. Sokolov's system by using an acoustic lens which focused the image of the resounded object onto the surface of a liquid and using a combined lighting system, which makes it possible to consider the relief on this surface either in the passing light or in the reflection.

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[1]Bergmann also considerably reevaluates the resolving ability of acoustical systems, affirming that it exceeds the resolving ability of the strongest immersion objects of a microscope [77].

[2]See also G. Spengler. DWP No. 11420, 1952.

A more perfected flaw detector is that developed by Schuster and described by Trommler [159, 160] for serial control of sheets of dimensions up to 2500 × 300 × 10 mm for the presence of stratifications. The flaw detector was made and is operated in the Zeiss factory in the German Democratic Republic. In this flaw detector visualization is realized by the interference method of Toepler.

Resolving power of the Schuster flaw detector when the setup is thoroughly damped can be brought to 1 mm, which permits obtaining photography of satisfactory quality.

The shadow flaw detector of Polman has already been mentioned. It is achieved with the original sound-optical converter, based on the known Rayleigh effect that nonspherical (flat, bacilliform) particles whose dimensions are considerably less than the wavelength, being weighed in the liquid medium in which elastic waves propagate are oriented so that their planes or axes become parallel to the wave front.

Polman's converter is very sensitive and gives a contrastive image, formed during a time measured in fractions of a second already at a field intensity of 10 W/m^2 which corresponds to a sound pressure of the order of 0.05 bar. The dynamic range in which the converter works without saturation exceeds 40 dB, resolving power approximately equals length of elastic wave.

Methods of visualization which we have considered provide direct conversion of a sound field into a visible image simultaneously over the whole area of a section of field. This conversion can be carried out, however, by other means — by scanning the considered hidden field image at points with transformation of sound wave energy into electrical energy and then, after amplification, into light energy. This method, used in television technology, has considerable benefits.

The first flaw detector, in which mechanical scanning of a hidden electrical image of a field on a receiving quartz plate with help of a capacitance commutator was used, was made in the form of a Nipkov disk (see Fig. 99) was developed and described by S. Ya. Sokolov [126]. This instrument allowed observation of the image of heterogeneity of a field on the screen of a neon tube, where quality of image corresponded to television technology of that time.

Further improvement of the system of mechanical scanning was made by P. V. Ponomarev [161]. He used pulse conditions of UZK radiation at 1-3.5 MHz, applied sound optics (spherical mirror and lens), and for scanning developed a square metallic probe oscillating simultaneously in horizontal and vertical planes with frequency 3 and 0.065 Hz, correspondingly. P. V. Ponomarev established that sensitivity of the device is 300 W/m^2 in water – 0.3 bar, resolving ability of device does not exceed several wavelengths in quartz, inasmuch as the slanted UZK incident on the quartz plate propagate along the plate, eroding the piezoelectric relief. Photographs obtained by P. V. Ponmarev show the principal possibility of the use of the method of mechanical scanning for controlling articles of simple configuration.

It is entirely natural that inasmuch as further development of technology of television was not by mechanical scanning, but by an improved way of using electron scanning, analogous ideas appeared in the region of ultrasonic defectoscopy.

This idea was first expressed[1] and carried out by S. Ya. Sokolov [163, 165, 166, 167]. One of the schemes proposed by him is shown in Fig. 126. A shadow image of heterogeneity in the resounded object using a system of acoustic lenses is projected onto a receiving quartz piezoelectric layer which is the bottom of a special electron-beam tube – a sound-electron converter. Inasmuch as pressure on quartz plate changes from point to point in accordance with irregularity of field intensity on a section, in different points of this plate charges of various magnitude will appear. These charges are taken from the nonmetallic internal surface of the plate with an electron beam emitted by an ordinary electron gun and scanning the surface of the plate per line. In such a way plate current of the sound-electron converter is modulated.

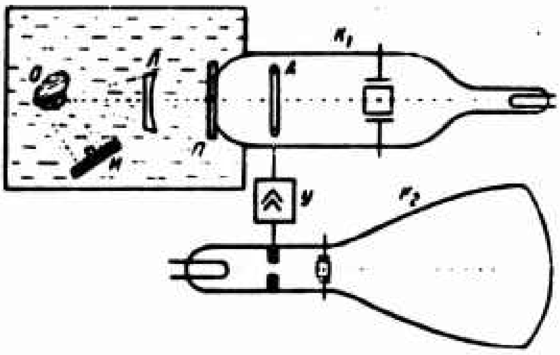

Fig. 126. Diagram of device for visualization of wave field by method of scanning by electron beam: И – radiator; О – reflector; П – receiver; У – amplifier; А – anode; $К_1$, $К_2$ – electron-beam tubes; Л - lens.

[1]See also S. Ya. Sokolov. Author's certificate No. 49426, 1936; No. 90236, 1949.

Further, through the amplifier this current joins the reproducing electron-beam tube (kinescope) in which the beam shifts synchronously with the beam of the sound-electron converter. Brightness of glow in every point of screen of kinescope changes in accordance with force of plate current of sound-electron converter or in accordance with distribution of intensity of wave field over a section. As a result of all this on screen of kinescope will appear image of structure of wave field, reproducing the form of the heterogeneity (defect) revealed in the resounded object.

As S. Ya. Sokolov shows, with such a device at 1000 MHz an image of heterogeneity increased by 10000 times can be obtained. On this basis S. Ya. Sokolov called the device an "ultrasonic microscope." This name however, absolutely does not correspond to functions executed by the instrument.

By microscope is usually understood a system making it possible to obtain a considerable useful increase i.e., an increased revealing thin pictorial details invisible to the naked eye. Maximum useful increase of microscope is determined by the resolving power of the system and can be calculated by means of division of resolving power of eye by resolving power of the considered system. Thus, taking resolving power of eye d_{Γ} equal to 0.3 mm (300 μm) and considering that resolving power of a contemporary optical microscope d_M, as already was indicated, is 0.2 μm, we obtain magnitude of limiting useful increase given by an optical microscope possessing lenses with minimum aberrations:

$$M_{max} = \frac{300}{0,2} = 1500.$$

It is possible to obtain with an optical microscope a greater increase, however, no new details of the considered image will be revealed, this will not be a useful but an "empty" increase, or in other words, an increased scale of image.

In order to increase limit of useful increase of a microscope it is necessary to increase its resolving power and this is possible only when waves whose length is considerably less than the wavelength of visible light are used for forming of image. It is known that by applying illumination of object by ultraviolet beams and special (quartz) optics passing these beams it is possible to increase

resolving power and consequently limit of useful increase of microscope approximately twice.

An electron microscope, in which waves whose length is approximately 1000,000 times less than the wavelength of visible light are used permits obtaining resolving power and limiting useful increase approximately two orders[1] more than in an optical microscope.

In the setup proposed by S. Ya. Sokolov the resolving power, and consequently the limit of useful increase are determined by the length of an elastic wave in metal, which even at 1000 MHz (and the use of UZK of such high frequencies for the flaw detection of metals must be considered as yet unreal) will be an order greater than the wavelength of visible light. If, moreover, we consider the low quality of contemporary acoustic lenses, it will become clear that we cannot talk about a useful increase of 10000 times.

Thus, the setup proposed by S. Ya. Sokolov is not a microscope, but a shadow flaw detector with image visualization of the observed defect and with the possibility of certain scale increase of this image. As such an instrument this device presents indubitable interest, opening a new path of development of ultrasonic defectoscopy. Such a device essentially increases sensitivity of instrument, inasmuch as there is the possibility of large amplification in the electrical channel. High speed of scanning permits observing not only an immobile but also a mobile image. Observation can be carried out not only in direct proximity from controlled article but also on a kinescope, transferred to a considerable distance, and also on several kinescopes in parallel and located at different points.

Constructuve realization of a sound-electron converter is connected with serious difficulties. First of all it is necessary to solve the problem of vacuum-tight connection of piezoelectric plate with body of converter in order to obtain a system not requiring continuous evacuation. Further, it is necessary to have a converter with sufficiently high threshold of sensitivity, with low level of set noises, and sufficiently large visual field.

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[1]Not by five orders as would have been possible to expect from the relationship of wavelengths, due to very low quality of magnetic lenses possessing considerable aberrations.

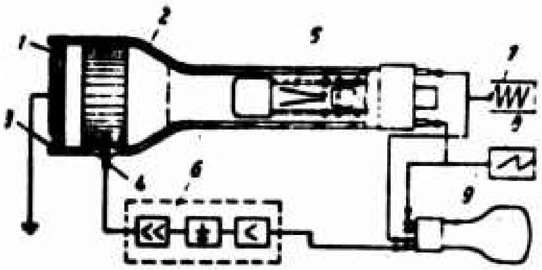

Fig. 127. Diagram of sound-electron converter [169]: a) piezoelectric plate; 2) body; 3) packing; 4) collector leadout; 5) electron gun; 6) amplifier; 7) line scan generator; 8) frame scan generator; 9) kinescope.

Works conducted in the USSR [168] have already given very serious results. One converter, developed by P. K. Oshchpkov, L. D. Rozenberg, and Yu. B. Semennikov [169], diagram of which is shown in Fig. 127, has a threshold of sensitivity of the order $3 \cdot 10^{-5}$ W/m^2, sensitivity near 0.02 μV/bar and visual field 85 × 85 mm. Amplitude response curve of the electron-acoustic converter[1], called by the authors ["UNIKON"] ("УНИКОН"), is linear in a wide range of sound pressures up to 70000 bar and more on imput [170].

In Fig. 128 and 129 are given photography of images obtained with the described converter by which it is possible to judge its resolving power.

Work on creation of methods and devices for visualization of a sound field continues in the USSR and abroad (basically in the German Democratic Republic). Of foreign work one should note created by Ardenne [171] a converter system in which UZK fall onto a thin (0.4 mm) layer of artificial rubber covering the thin (1 mm) glass bottom of the converter. Absorbing the UZK, the rubber is heated and heats the photocathode on the bottom of the converter from within. The photocathode emits electrons, forming an image on the converter screen.

Sensitivity of such a converter at 5 MHz is near 1000 W/m^2.

There is certain interest in the original system proposed by Martin in [172] which in distinction from preceding systems, image of structure of wave field is formed as a result of electron scattering upon elastic reflection from surface of the piezoelectric plate excited by the investigated wave field, and having due to this on the surface relief characterizing structures of this field.

Judging by first results this system of visualization of structure of wave field possesses fair characteristics.

It is possible to expect that further improvement of methods and devices allowing visualization of sound images soon will give the researcher and plant

[1]The authors called their device an electron-acoustic converter (EAP), however, considering the use of this device for one-sided conversion, it is more correct to call it a sound-electron converter.

worker a reliably effective and sufficiently sensitive shadow flaw detector — an automatic machine of high productivity.

However, even now the shadow method utilized in the primary and mirror variants, solves a whole number of problems of the control of different articles (fuel elements of atomic reactors — for lag of shell, pressed rods — for the presence of extrusion shrinkage cavities rolled sheets — for stratifications, welded pipes — for defects of a welded seam, multilayer disks and rubber covering — for stratifications, metallic ingots, large scale blocks from plastic for cracks, etc.) making it possible to reveal in them various kinds of defects including those of very small size.

IV

RESONANCE METHOD OF ULTRASONIC FLOW DETECTION

1. Physical Bases of Property

The basic problem of the resonance method and instruments (flaw detectors thickness gauges) working on the principle of this method is sufficiently high quality control of articles of comparatively small thickness from metals, porcelain, glass, ceramics and other materials.

The resonance method can be used to measure thickness of an article (accessible on one side) and also to reveal zones of corrosive damage, zones which are solderless or uncemented in sheet compounds, stratifications in thin sheets, in bimetals, to determine level of liquid in a closed vessel, etc.

Working by the resonance method, changes of operating conditions of radiating [UZK] (УЗК) of the piezoconverter are observed in connection with change of load on it at the time of appearance of standing waves. Standing waves appear under certain conditions of propagation of oscillations (in the given case — elastic longitudinal oscillations, although in principle the resonance method can be based on the use of elastic oscillations and other types) in the surrounding medium, as a result of a direct wave system or one reflected from any barrier. Moreover, in an idealized — homogeneous, isotropic medium and when UZK are not damped points where there are no oscillations of particles (nodes) and points where they are occur with maximum intensity (antinodes) are observed. In specific moments of time a half period apart oscillations are absent (amplitude of displacement of all points passes through zero). Nodes and correspondingly antinodes are half a wavelength from one anothér. Nodes from an antinode are a quarter wave apart.

Formation of standing waves is possible only in the case of resonance, i.e., coincidence of frequency of external perturbing force with frequency of natural oscillations of system. Between thickness d of article and length λ of elastic wave in the material of an article surrounded by a medium with smaller specific wave impedance should be observed the relationship[1]

$$d=\frac{n\lambda}{2}=\frac{nc}{2f}, \tag{46}$$

where n — integer determining the order of harmonic of oscillations (at resonance on basic frequency n = 1), c — rate of propagation of UZK in material of article, f — frequency of UZK.

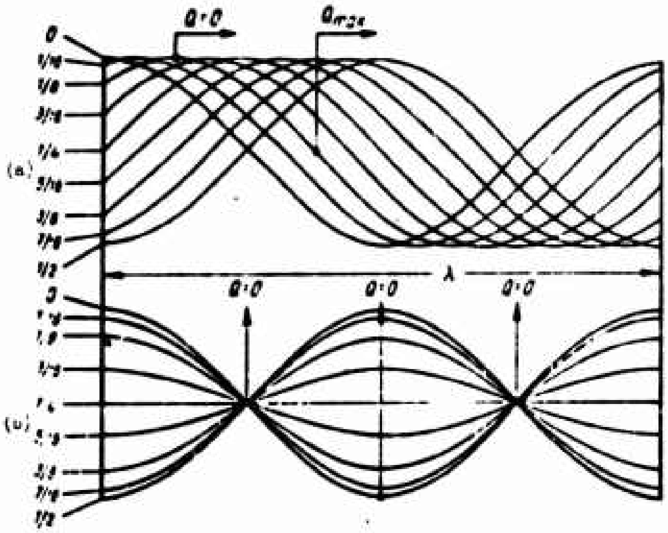

Fig. 130. Photographs of traveling (a) and standing (b) waves.

A photograph of a standing wave can not differ from that of a traveling wave (Fig. 130) if it is made not at the time of transition of amplitude of oscillations through zero value. A standing wave, formed as a result of interference of sinusoidal waves, also is sinusoidal with the same length and period but with considerably larger amplitude in the antinode.

[1]We do not consider the less interesting case when after the reflecting boundary is a medium whose specific wave impedance is more than for the medium from which UZK fall onto this boundary. For this case the condition of resonance is different:

$$d=(2n+1)\lambda/4.$$

Points located between node and antinode oscillate with intermediate values of amplitudes. These amplitudes are constant for every separate point and are distributed in space by sinusoidal law. This can be graphically observed by comparing photographs of standing waves made consecutively over short intervals of time. Within the limits of every half-wave (from node to node) phase 3 of oscillations of all points are identical; in nodes there is a phase jump of 180°.

Thus, the first distinction of a standing wave from a traveling wave is generality of phase and distinction of amplitude of separate oscillating points (for a traveling wave this is characteristically the opposite: all points oscillate with identical amplitude but not simultaneously and with different phase).

The second and most essential difference of a standing wave is a completely different characteristic with respect to energy transfer. As is known, in a traveling wave displacement of particles is equal to zero when their rate of oscillation v and magnitude of stress σ (and deformation) are maximum, and conversely at the time of maximum displacement rate and deformation are equal to zero (since neighboring, infinite close particles are identically displaced, and consequently there is neither extension nor compression).

In a standing wave displacement and deformation change cophasally and rate of oscillation outstrips them by a quarter-period.

If a standing wave is photographed when oscillation speed of all points is equal to zero, for any point displacement and deformation will be the highest possible for this point. Absolute values of maxima of displacement and deformation do not coincide, since where displacement is maximum deformation is zero and conversely. Nodes of deformation coincide with antinode of displacement and rate of oscillation. Antinodes of deformation coincide with nodes of displacement and rate of oscillation.

The flow value of energy through area S is determined from the expression $Q = S\sigma v$. In a traveling sinusoidal wave energy flow will be maximum in every moment of time where displacement is equal to zero (σ and v are maximum), and conversely energy flow will be equal to zero where displacement is maximum (σ and v are equal to zero). Maximum of flow will consequently shift in direction of wave propagation.

In a standing wave energy flow is equal to zero in any moment of time in nodes of stress and deformation ($\sigma = 0$) and in nodes of rate of oscillation and displacement ($v = 0$). Thus every section of a rod whose length is equal to the quarter-wave

included between node of deformation and the nearest node of rate of oscillation does not exchange energy with neighboring sections. It constitutes its own kind of "section" general energy of which is constant.

This energy only twice per period passes from nodes of deformation (antinode of oscillation rate) to antinode of deformation (node of oscillation rate), being transformed, moreover, from kinetic into potential and back. In moments when oscillation rate is equal to zero energy is completely potential; when deformation is equal to zero (and oscillation rate is maximum) energy is wholly kinetic.

What was said pertains, however, only to the ideal standing wave formed in case of interference of two approaching traveling waves of absolutely identical length and amplitude. The standing wave ratio, determined by ratio of amplitude of oscillations in an antinode to amplitude of oscillations in a node is equal to infinity. In real conditions amplitudes of incident and reflected waves cannot be identical, since due to geometric divergence of UZK and their damping amplitude of reflected wave is always somewhat less than amplitude of the incident wave. Therefore if frequency of UZK does not change continuously as in the operation of the extremely simple instrument of Erwin and Rassweiler [173], as a result of interference of incident and reflected waves along with the standing wave is observed also a traveling wave in the direction of propagation coinciding with the incident wave. The traveling wave transfers energy in this direction as a result of which total amount of energy which had to be included in the ideal standing wave, and consequently the standing wave ratio, decreases.

At the time of resonance and formation of standing wave in the controlled article input impedance of load decreases (reactive component of becomes zero), amplitude of elastic oscillations in article sharply increases, energy content taken by article from generator is increased, shunting action of piezoelectric converter increases, as a result of which much damping is introduced into the generator circuit. This in turn leads to decrease of amplitude of electrical oscillations in generator, increase of anode and decrease of grid currents in it and can be noted by an indicator. Naturally change of enumerated parameters, i.e., sensitivity of entire device is greater the greater the coefficient of the standing wave and the greater the quality of all elements of the device, constituting oscillatory systems of circuits of generator and amplifier of piezoelectric converter and finally the controlled article itself.

2. Equipment and Method of Control

A simple diagram of an ultrasonic resonance flaw detector thickness gauge is shown in Fig. 131. The vacuum tube oscillator feeds by alternating high frequency voltage piezoconverter П. The latter, applied (through layer of contact lubricant) to tested article И, excites in it elastic oscillations.

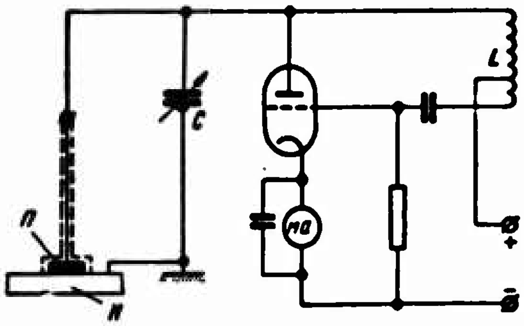

Fig. 131. Fundamental diagram of a simple ultrasonic resonance flaw detector thickness gauge: C – capacitor; L – inductance coil; И – controlled article; П – piezoelectric converter.

If changing capacitance C, frequency of generator is smoothly changed, at a defined frequency the condition for formation of a standing wave can be carried out. There will be observed a sharp deflection of the milliammeter needle.

If approximate thickness of article is known and parameters of generator are selected so that only one resonance, corresponding to fundamental frequency is considered, then calculation of thickness is very simple:

$$d = \frac{\lambda}{2}, \text{ or } d = \frac{c}{2f}.$$

However, inasmuch as resonance can be noted not only on the fundamental frequency, but also on harmonics, the resonance instrument does not always directly indicate thickness of measured article; in a number of cases it is necessary to resort to calculations or make use of special graphs.

So, if scale is graduated in thicknesses, calculation can be made by the formula

$$d = \frac{m \cdot D_n \cdot D_{n-m}}{D_n - D_{n-m}}, \tag{47}$$

where D_n and D_{n+m} – thicknesses corresponding to two arbitrary readings, m – number of intervals between these readings.

If, however, scale is graduated in frequencies, inasmuch as difference of frequencies between any two neighboring harmonics equals the fundamental resonance frequency, calculation can be made by the formula

$$d = \frac{mc}{2(f_{n+m} - f_n)}, \tag{48}$$

where c — rate of UZK in material of article; f_n and f_{n+m} — frequencies corresponding to two arbitrarily taken readings; m — number of intervals between these readings (difference of numbers of harmonics).

A resonance flaw detector can work also with a sound indicator [174, 175], as was done in a recent model of the Audigage [Branson, USA] and in the "Type 1101," manufactured by the English firm Dawe Instruments Co.

So that it was possible to determine aurally the change of plate current, the generator is modulated by audio frequency (400 Hz). Upon formation of standing waves plate current is increased and a sound is audible in the telephone.

It is necessary to note that both the considered variants of the scheme of the resonance flaw detector possess very high sensitivity, inasmuch as standing wave ratio upon interference of oscillations of identical and constant frequency can have sufficiently large values. However, the fact that thickness is measured by means of "searching" the standing wave, using rotation of the capacitor, is an essential deficiency — it always is possible to omit one or another harmonic, control of acoustic contact is impossible. It is difficult to exclude the influence of different side factors which can cause deflection of instrument needle or change of sound in telephone line which is not connected with formation of standing wave. Determination of moment of resonance by force of sound in telephone is very subjective. It is advisable, therefore, in the instrument setup to provide automation of investigation and an improved indicator allowing observation of all harmonics simultaneously.

Resonance flaw detectors for quality control of railroad rail joints [176], developed by Branson (USA) and later by Mitsubishi (Japan) provided frequency modulation of UZK, facilitating detection of resonance. However, inconveniences connected with presence of a sound indicator in these instruments are not removed.

A flaw detector with automatic search and oscilloscopic indicator has indisputable advantages in the sense of convenience of work, [177] although sensitivity of such a flaw detector is lower, as will be shown further, due to decrease of standing wave ratio. The block diagram of such an instrument is shown in Fig. 132. Frequency modulated generator [GChM] (ГЧМ) excites piezoelectric converter П.

Ultrasonic oscillations of changing frequency, radiated by piezoelectric converter, are introduced into article И, propagate in it, and are reflected from the opposite surface.

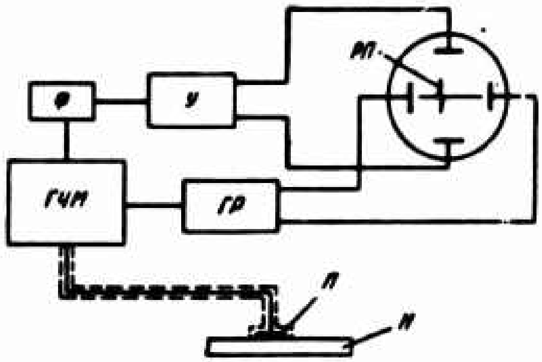

Fig. 132. Block diagram of an ultrasonic resonance flaw detector-thickness gage with automatic search and an oscilloscopic indicator.

Increase of plate current of generator, occurring when standing waves appear in the articles after passage through filter Ф, delaying the low frequency component of current, and amplifier Y is observed on screen of oscilloscope in the form of characteristic overshoots (resonance peaks) [RP] (РП). Scanning by sweep generator [SG] (ГР) is synchronized with change of frequency of generator GChM so that to every point on the time axis corresponds defined frequency of generator. Scale on screen of electron beam tube permits reading off the distance from beginning of scanning to the corresponding peak and can be graduated in frequencies or thicknesses.

Modulation of frequency of generator in such an instrument is most simply done by continuous rotation of axis of circuit capacitor with a small motor. For this a variable straight-line frequency capacitor of special construction is necessary, allowing 360° rotation and well balanced.

Such a construction is incorporated in the instruments of Carlin [177] and also in the attachment [PT-1] (ПТ-1), developed by the author with his colleagues for the [86IM-2] (86ИМ-2) [178], and resonance thickness gauge [URD-3] (УРД-3) [179], differing by the use of a synchronous motor for rotation of capacitor.

These instruments work very stably, allowing measurement with sufficient accuracy, and have obtained wide application. One of the best foreign instruments of such type is the Reflectogage [Sperry, USA]. However the presence of rotating parts considerably worsens exploitational characteristics of instruments of similar type and frequently hampers reading.

This led the author and his colleagues to the necessity of developing in 1954

an ultrasonic resonance flaw detector of thickness gauge[1] [V4-8R] (B4-8P), in which for the purpose of improvement of conditions of work, reliability of construction and exploitational characteristics of the instrument constructive solutions are different from those in existing instruments [181].

Basic distinctions of the V4-8R[2] from those known earlier are methods of realization of frequency modulation and starting the scan generator. In the V4-8R frequency of modulation carried out by means of changing the coil inductance of the generator circuit while magnetizing its core by an alternating magnetic field. Toroidal form, special system of winding of this coil on an annular core from high frequency magneto dielectric, and possibility of adjusting the magnetizing current permit change (deviation) of frequency in wide limits.

Such a system of frequency modulation permits also managing without rotating parts and rubbing contacts, which essentially increases reliability of construction.

Starting and stopping the scan in the V4-8R is done at exact coincidence of frequency of generator with frequencies corresponding to fixed points of beginning and ending of the scan. This is done with a quartz filter tuned to the higher of these frequencies and passing at the time of coincidence of frequency of second harmonic of generator with this highest frequency — a voltage pulse utilized for starting the scan, and then at coincidence of fundamental frequency of generator with frequency of filter — a second pulse which stops the scan.

Thus beginning and ending the scan in the instrument V4-8R are strictly fixed in frequency and are not shifted during a frequency drift of the generator connected with replacement of tubes, which considerably increases stability of instrument readings and permits stable and sufficiently accurate graduation of the instrument directly with respect to thickness.

Graphs connecting measured thickness with resonance frequency $\left(d = \frac{nc}{2f}\right)$, expresses an inversely proportional dependence and in linear scale with respect to both coordinates is represented (for different frequencies) by a family of hyperbolas. To construct such a graph a great number of calibrated samples is required. If,

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[1]D. S. Shrayber, G. V. Prorokov, B. G. Golodayev, Yu. V. Lange, L. A. Auzin. Author's certificate No. 105224, USSR, 1954.

[2]Development of the URD-3 and V4-8R was done jointly with the OKB (V. P. Uftyuzhaninov, L. A. Auzin, G. Ye. Bessonov).

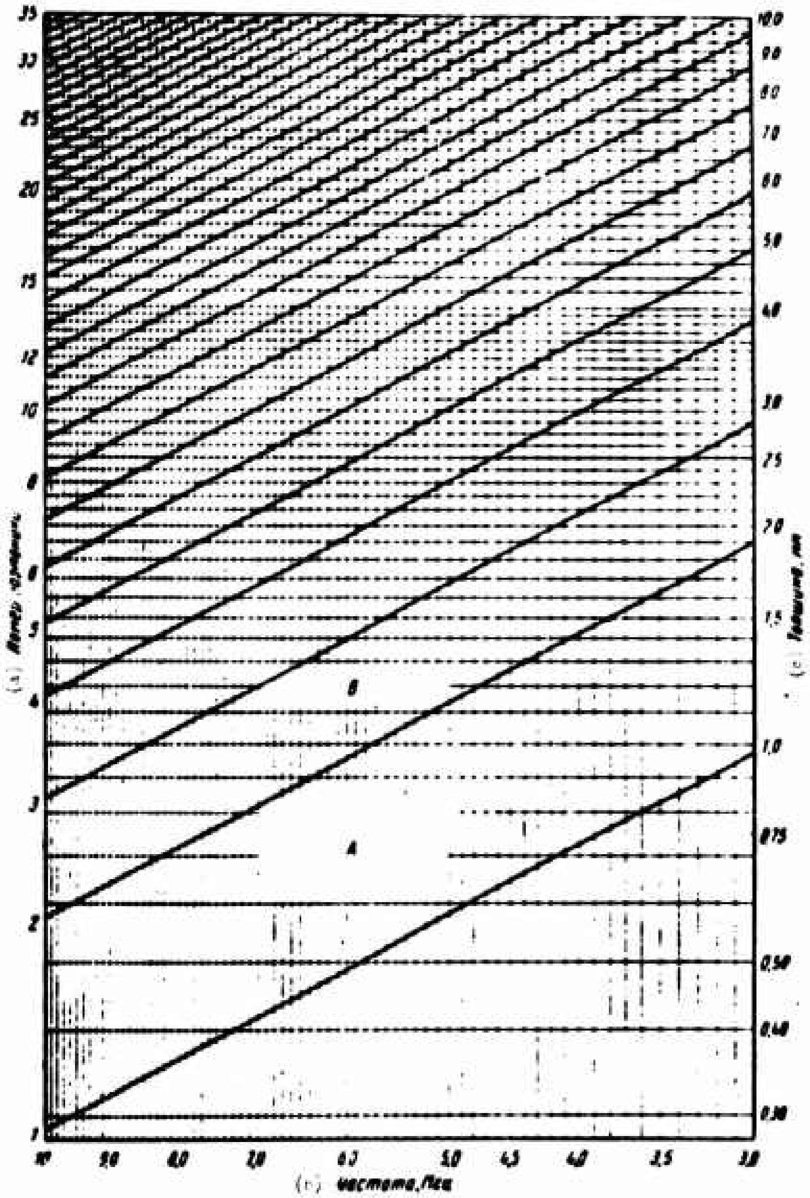

Fig. 133. Graph of dependence of resonance frequency on thickness of part.
KEY: (a) number of harmonic; (b) frequency, MHz; (c) thickness, mm.

however, a logarithmic scale is used, the graph will be represented by parallel lines inclined to axes of coordinates at a defined angle (Fig. 133). The lower line on this graph, for c = 5820 m/s, corresponds to resonance on the fundamental frequency and the second to resonance on the second harmonic; further lines go in order of growth of number of harmonics, while distance between lines gradually decreases. Such a graph can be constructed according to two calibrated samples.

In the V4-8R the first issue of graph was shaped in the form of a plane table developed by the author with mobile scale allowing rapid and exact to determination

of thickness of article according to instrument readings. In instruments of subsequent issues the plane table is replaced by the more convenient calculation disk proposed by G. Ye. Bessonov.

The described principle features of the V4-8R pertain to the most important of its parameters determining quality of work of instrument.

In designing a resonance flaw detector thickness gauge it is necessary to select correctly also the working part of the generator, number and limits of frequency ranges, magnitude of deviation of frequency, frequency of modulation, type and design of searching head.

During the selection of these parameters it is necessary to originate from basic purpose of the instrument.

Selection of working part is dictated by the following conditions: a) condition of introduction of UZK into metal; b) directivity of introduced beam of UZK; c) damping of UZK in metals d) maximum thickness of article; e) necessary accuracy of measurement.

Soviet and foreign practice of work with the resonance flaw detector thickness gauge permits recommending for the solution of different problems the use of UZK of low (0.5-2.5 MHz), average (2.5-7.0 MHz), and high (7.0-25.0 MHz) frequencies.

With increase of frequency of oscillations accuracy of measurements increases, but introduction of oscillations into metal is hampered, damping is intensified, and requirements for cleanness of treatment of surface are increased. With decrease of frequency (for assigned dimensions of radiator) directivity of beam becomes worse and angle of divergence increases. This leads to decrease of standing wave ratio, to appearance of additional resonance peaks at frequencies somewhat different from the fundamental resonance, picture on screen worsens, and its deciphering is hampered. Impairment of directivity upon lowering frequency can be compensated by increase of dimensions of radiator; however, resolving power of instrument and conditions of creation of reliable acoustic contact become worse. In the V4-8R working frequency in the midrange is 4.5 MHz.

Quantity and limits of frequency ranges are determined depending upon assigned specific conditions of production of the range of measured thicknesses (for the V4-8R it is 1-15 mm), permissible error of measurements, and magnitude of deviation of frequency of generator. With a large number of ranges, and consequently with a small deviation of frequency, error of measurements can be made minimum. In

conditions of production control of several thicknesses is possible; in other cases smooth covering of a considerable range is required. As will be shown below, in the second case the scheme is more complicated.

Requirements for the V4-8R permit being limited to one range.

Magnitude of deviation of frequency, i.e., limits of change of carrier frequency of generator is determined from the following considerations. If we originate, for instance, from a working frequency of 2.5-7 MHz, resonance on the fundamental frequency can be fixed only in a range of thicknesses of the order 0.43-1.2 mm. Larger thicknesses are measured on harmonics. If thicknesses measured starting from these magnitudes grow smoothly, to cover the whole range it is necessary to have a change of frequency within the limits of not less than one octave, i.e., twice. If this condition is not ensured the range of thicknesses will not be covered and in specific sections there will be collapses in which it is impossible to measure. Thus when frequency changes the within limits of 5-7 MHz there will be collapses in intervals of 0.58-0.83 mm and 1.25-1.33 mm (zones A and B on graph Fig. 133). In these intervals resonance is not noted and thickness is impossible to measure. In the V4-8R frequency changes within the limits 3-6 MHz. This ensures continuity of range of measurements starting from the minimum thickness on which resonance of 0.485 mm can take place.

However, here one should consider one more important circumstance. Obtaining on the instrument screen resonance peak corresponding to a frequency of, for instance, 5 MHz, and not knowing approximate value of measured thickness, it is impossible to determine it uniquely: actually, it can be either 0.58 or 1.16 mm.

So that thickness is determined uniquely it is necessary that on the instrument screen not less than two resonance peaks can be seen simultaneously. Uniqueness of measurement, as Yu. V. Lange showed [182] is guaranteed therefore only starting from thicknesses for which magnitude deviation corresponds to

$$\frac{f_{max}}{f_{min}}=\frac{n+1}{n-1}, \qquad (49)$$

where n — highest number of harmonic on which at a given thickness resonance is noted. As may be seen from graph Fig. 133, when frequency changes from 3-6 MHz unique measurement is possible only starting from a thickness of 1.44 mm, i.e., thickness for which at 6 MHz resonance on the third harmonic is observed. This corresponds to change of frequency by twice, provided in the V4-8R:

$$\frac{f_{max}}{f_{min}} = \frac{3+1}{3-1} = 2.$$

If it is necessary to ensure uniqueness of measurements starting, for instance, from a thickness of 1 mm, then as follows from the graph this can be done only at a deviation of frequencies equal to three (3-9 MHz). At a smaller thickness deviation should be equal to three and range displaced still more in the direction of high frequencies.

Deviation exceeding 2.5-2.7 is difficult to carry out; its use is possible only in the control of articles from materials of high quality. Uniqueness of measurement in resonance flaw detector thickness gauges begins with a thickness somewhat exceeding the minimum value of working range, if this value is sufficiently small. If, however, the minimum thickness being measured is larger than that indicated (for instance 2-3 mm), measurement is made only on harmonics and a change of frequency (deviation) can be less, and still less the greater the minimum thickness, i.e., the higher the order of harmonics on which measurement is conducted. Necessary deviation during measurement of a fixed thicknesses also is small.

During work with small deviation frequencies a gain in sensitivity of instrument can also be obtained.

As already was noted, sensitivity of instruments with automatic search, i.e., with frequency modulation, is less than for instruments with "manual" search, since standing wave ratio decreases due to impairment of interference conditions. A standing wave appears when two waves propagating toward another combine so that in any point of space phases of the meeting waves coincide. In an instrument with frequency modulation this condition is not executed — in any point waves meet having variable difference of phases as a result of which the standing wave ratio decreases. This difference of phases is proportional to frequency drift of UZK in a given point their propagation time to reflecting surface and arrival at this point.

Departure frequency is determined by speed of modulation, and consequently grows with increase of deviation and with increase of frequency of modulation, and of course, with increase measured thickness. Thus, if frequency changes with constant speed from f_{min} to f_{max} during time T, speed of modulation a will be equal to deviation $f_{max} - f_{min}$ divided by time

$$a = \frac{f_{max} - f_{min}}{T};$$

Hence frequency drift during time $t = \frac{2d}{c}$ will be

$$\Delta f = at = \frac{2ad}{c} = \frac{2d(f_{max} - f_{min})}{cT}. \qquad (50)$$

therefore, to increase sensitivity of instrument, magnitude of deviation, and also frequency of modulation must be lowered. Lowering of frequency of modulation, however, is limited because the image on the screen starts to blink. In the V4-8R frequency of modulation is 50 Hz and speed of modulation is ~500 Hz/μs.

Benefit of work with a small deviation is also an increase of accuracy of measurements, which is confirmed by the dependence derived by Yu. V. Lange [182], which makes it possible to determine relative measurement error γ:

$$\gamma = \frac{\Delta l_{min}(f_{max} - f_{min})}{l \cdot f} \cdot 100\%. \qquad (51)$$

where Δl_{min} — displacement of resonance peak on screen of instrument, correctly noted by operator; l — scale length of instrument; f — frequency on which resonance peak appeared.

If we take Δl_{min} = 1.5 mm, for the middle part of the V4-8R scale error should not exceed 1%. Experiment has showed that in the V4-8R of serial production the measuring error is less than 1%, which was confirmed also during state tests of this instrument conducted in 1955.

The given formula does not consider all factors affecting accuracy of instrument readings. This accuracy, which theoretically can be brought to very high values (for instance at f = 25 MHz the theoretical value of maximum error is measured in hundredths of a percent), in practice is not realized due to inevitable scattering of values of speed of propagation of UZK in material of the controlled article (especially a poured one), limited resolving power of indicator, inconstancies of acoustic contact leading to change of resonance frequency of controlled article, and also due to inaccuracy instrument calibration.

Maximum error of measurements accessible in real conditions is 0.1-3.0% of the measured thickness, depending upon frequency of UZK.

It is necessary, however, to consider that work of instrument on limiting high frequencies of the order of 25 MHz is complicated by certain inconveniences. Thus, for instance, in this case it is impossible to connect piezoconverter to instrument with a long cable. Inasmuch as capacitance of cable increases general capacitance of the generator circuit, on 25 MHz length of cable must be reduced to half a meter

and less. It becomes difficult to measure articles of large dimensions and to maintain constant acoustic contact. Requirements for constancy of acoustic contact and consequently, frequency of treatment of surface of article in work at high frequencies sharply increase. When measuring small thicknesses on high frequencies the error introduced by oscillations of thickness of layer of contact lubricant increases inasmuch as this thickness approaches the measured thickness.

In general, for exact results constant pressure of piezoconverter against article and consequently constant thickness of layer of contact liquid must be ensured (usually — light oils, water, sometimes in the control of articles with a more rough surface glycerine with the addition of an emulsifier). In the V4-8R, for instance, constancy of pressure is ensured by the force of a special spring built into body of head and pressing piezoconverter to article with constant force independently of force pressing body of head to article.

Construction of searching head in many respects determines work of instrument. Usually searching heads with a flat (Fig. 134a) quartz piezoconverter are used (X-cut plate). In a number of cases, for instance, in the manufacture of plates with a groove (Fig. 134b) or curved plates whose curvature is coordinated with curvature of controlled articles (Fig. 134c), artificial piezoelectric crystals (barium titanate) can offer greater possibilities. However, an experimental check of such searching heads showed that application of a piezoelectric element from barium titanate leads to lowering of sensitivity due to its low quality and consequently the decrease of the standing wave ratio and the bent curved piezoelectric element is very nondurable and of little use for measurements in industrial conditions.

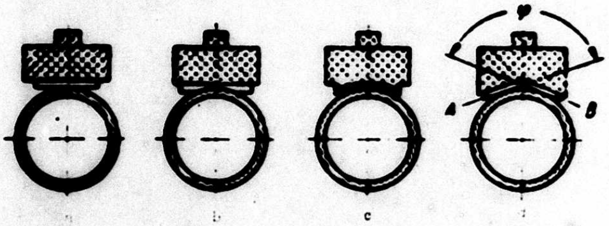

Fig. 134. Diagrams of carrying out the acoustic contact in work by the resonance method [183].

Resonance frequency of a piezoelectric converter must lie outside range of generator and be somewhat higher than its upper limit. This is profitable because for quartz with a high resonance frequency (i.e., thinner) coordination of resistance of radiation with internal resistance of generator is improved.

Form and dimensions of piezoconverter have a large influence on quality of acoustic contact and resolving power. The most widespread form of plates — round —

is not always the most profitable. To increase area of contact surface, and consequently to increase sensitivity of instrument in working with articles of cylindrical form, best results sometimes come from right angle plates, if they are used with the long side in the direction of the generatrix of the cylinder. However this measure is effective only for a small curvature of surface of the controlled article. For a great curvature sensitivity increases insignificantly and accuracy noticeably drops. Increase of area is advisable in work on low frequencies, since divergence of UZK somewhat decreases, lowering accuracy of measurements and sensitivity.

On average frequencies area of plates usually is 2-3 cm^2, and its decrease worsens work of instrument due to divergence of UZK and the connected decrease of the standing wave ratio.

Measured thicknesses of wall of cylindrical articles with a diameter <20 mm is a more complicated problem which it is impossible to solve using the usual searching head touching the surface of the pipe along the generatrix of the cylinder. With such "linear" contact UZK are transmitted from searching head to article through layer of contact lubricant of variable thickness (Fig. 134a). With increase of thickness of liquid layer effectiveness of transmission of UZK sharply decreases. Besides, as follows from Fig. 135 only beams introduced into the wall of the pipe along the axis of the field of the piezoconverter do not experience refraction; others are refracted more strongly the farther they are from the axis. This leads to a noticeable decrease of the standing wave ratio and of sensitivity.

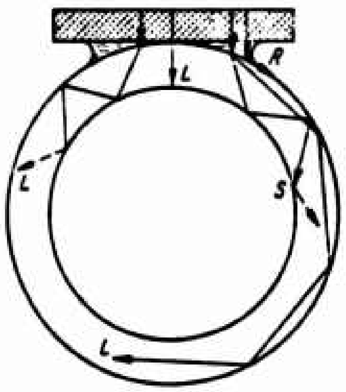

Fig. 135. Refraction of UZK during a change of thickness of small diameter tubes with the help of a flat piezoelectric element: L — longitudinal; S — shear; R — surface wave.

Moreover as a result of transformation there appear shear, surface, and normal waves, propagating along circumference of pipe. The piezoconverter takes them in the form of interference; therefore in the control of pipes of small diameter resonance on longitudinal oscillations is observed only in the small volume of the pipe near axis of piezoconverter and appears indistinctly; amplitude of resonance peaks on screen turns out to be commensurable with level of interferences and consequently sensitivity drops still more.

To increase sensitivity of instrument when measuring thickness of the wall of pipes of small diameter, I. N. Yermolov developed [183] a so-called "dihedral" searching head design (Fig. 134d). This head has two piezo elements located on the planes of a dihedral angle. The head is placed on the article so that both edges touch the surfaces of the pipe along the generatrix. Thanks to this the resonance volume of the article increases by twice and correspondingly sensitivity of instrument increases. Dihedral angle φ is 165^{o}, which ensures location of points of contact (A, B) of piezoplates with pipe a small distance from each other and permits in laboratory conditions measurement of thickness of wall of pipes from 6 mm in diameter with an error of the order of 2% for a 0.36 mm minimum thickness of wall.

If, however, angle between piezo elements in the "dihedral" head is decreased, the distance between points A and B increases and instrument will give a large error, since in essence two measurements will be obtained, and in case of a noticeable difference of thicknesses of the article in these points the result will be averaged.

Similar problems are solved considerably more effectively with the use of the immersion variant of the resonance method, permitting continuous and sufficiently rapid control during manufacture and control.

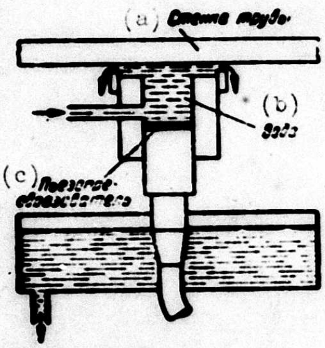

Fig. 136. Setup for measurement of the wall thickness of a pipe by the resonance method in the immersion variant [184]. KEY: (a) wall of pipe; (b) water; (c) piezoelectric converter.

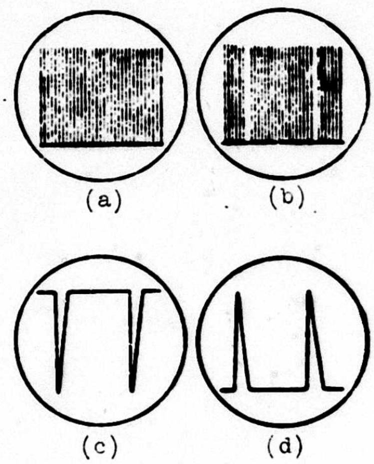

Fig. 137. Images on screen of resonance flow detectors during the measurement of wall thickness of a pipe according to the diagram on Fig. 136: a — resonance peaks in water in the absence of the controlled pipe; b — absence of resonance peaks on specific frequencies when the controlled pipe is present; c, d — images of pipe on screen.

The essence of this method, first described by Harris [184, 185] and then Leijson [186], is that supply of UZK from piezoconverter to wall of controlled pipe is produced through a layer of water of considerable thickness (Fig. 136). If the upper surface of the layer touches air (controlled pipe is removed) on the instrument screen resonance peaks will be seen (Fig. 137a), the number of which (N) is easy to determine by the formula

$$N = \frac{(f_{max} - f_{min})d}{7{,}5 \cdot 10^4}, \tag{52}$$

where f_{max} and f_{min} — maximum, and correspondingly minimum frequency of oscillations of frequency modulated generator (Hz), d — thickness of layer of water (cm).

For the V4-8R, for instance for a 1.5 cm layer of water the number resonance peaks on the screen will be

$$N = \frac{3 \cdot 10^6 \cdot 1{,}5}{7{,}5 \cdot 10^4} = 60.$$

If the upper surface of the layer of water touches the wall of the controlled pipe, in the wall appear resonance phenomena. The pipe works as a filter tuned on a defined frequency. Correspondingly on these frequencies the layer of water ceases to resonate. As a result the picture on the screen of the instrument changes — "collapses" appear on defined frequencies (Fig. 137b), and if the number of peaks is selected sufficiently large, thickness of wall of pipe can be counted off according to the position of sharp collapses of the rounding merged resonance peaks. If in the resonance thickness guage there is a special inverter, "negative" peaks (Fig. 137c) can be turned into positive and on the screen the usual convenient picture is obtained (Fig. 137d).

The immersion variant of the resonance method is very promising; however it has not yet obtained its due recognition and in industry basically the contact variant is used. For the creation of reliably working searching heads thorough solution of questions connected also with durability is required. Design of the searching head should ensure correct operation of both the electrical and mechanical element of the instrument. In initial designs of foreign searching heads for resonance flaw detector thickness gauges on the plate of the piezoelement was a metallic electrode only on the "back" side. To this electrode was soldered the centrical wire of the cable from the generator. The cable casing, adjoining the second pole of the generator output, was soldered to the metallic body of the head.

When the head is pressed to the article, the field acts on the piezoelement through a layer of contact lubricant. Changes of thickness of this layer led to fluctuations of sensitivity, and absence of a constant contact created instability in work. A unique property of such a design is that it is not necessary to protect piezoelement from wear, since the quartz itself is sufficiently wear resisting.

In searching heads of Soviet constructions both surfaces of piezoelement are metallized and to them both wires from the generator are soldered. Thus the electrical circuit of the piezoelement is closed independently of presence of contact between body of head and article. However, inasmuch as the external electrode on the radiating surface, the piezoelement is not wear resisting, it should be specially protected. Design of searching head should therefore ensure reliable protection of piezoelectric plate from damage or wear when rubbing the surface of the investigated part. In the V4-8R, for instance, the searching head is a quartz plate of X-cut 18 mm in diameter, 0.31 mm thick, which corresponds to a frequency of 9 MHz. This plate is glued on one side to the support body protecting the plate from brittle fracture, on the other — to the cap from stainless steel 0.1 mm thick protecting it from wear.

Selecting material for protection of piezoelement from abrasion is not a simple problem. A shield in the form of a limiting thin plate from a material possessing high resistance to wear and suitable acoustic characteristics would be ideal. Stainless steel as a shield can be used only with a small thickness (0.08-0.1 mm). With increase of thickness sensitivity of head drops and resonance phenomena are observed in the protective plate itself, which hampers reading.

In foreign designs of heads for protection besides stainless steel also aluminum, quartz, plastics and ceramics are used.

In 1957 the author and N. V. Babkin developed a design searching heads with a shield from beryllium,[1] which turned out to be the most suitable in the combination of a series of mechanical and physical characteristics.

Searching heads with a beryllium shield to the V4-8R have been widely introduced in industry and operational experience has showed their high qualities — great sensitivity and excellent resistance to wear.

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[1]D. S. Shrayber, N. V. Babkin. Author's certificate No. 120948, USSR, 1957.

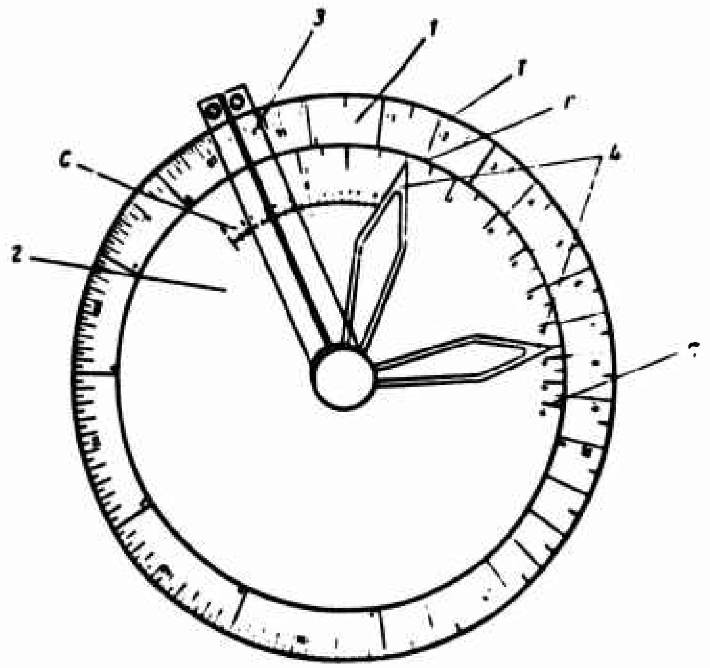

Fig. 138. Logarithmic slide rule for determination of thickness according to readings from the V4-8R: 1 — ring; 2 — center circle; 3 — main sight; 4 — auxiliary sights; Г — scale of instrument readings; Г' — scale of harmonics; T — scale of thicknesses; C — scale of speeds.

Instrument readings, as already was indicated are obtained by either calibration graphs or a logarithmic plane table, or its evolution — the circular slide rule in the V4-8R (Fig. 138).

An analogous slide rule is in one of latest models of the "Audigage," manufactured in 1958 in the United States.

The slide rule permits determining measured thickness with sufficient accuracy; however, work with it requires a relatively highly qualified operator and considerable expenditure of time.

3. Contemporary State and Development of the Resonance Method

At present in USSR and abroad development of theoretical bases of resonance method is being carried out; a number of reliable flaw detector thickness gauges have been created and method of working with them mastered.

Of Soviet instruments resonance flaw detector thickness gauges V4-8R and the URD-3, developed by the author with his colleagues, and also the [UZT-4M] (УЗТ-4М), [URT-5] (УРТ-5) and URT-6, developed by the TsNIITMASh.

It is necessary to note that in one of latest developments of the TsNIITMASh the URT-6 design of the magnetic frequency modulator is very successful. Use for

core of modulator of annealed high frequency magnetodielectric "oxyfer," a powder of high dispersivity, made it possible to realize a frequency deviation of three, to reach a considerable lowering of the level of electrical noises of the instrument, and consequently an increase of its sensitivity to the level necessary for control of thickness of walls of pipes 10 mm in diameter.

Abroad several models of ultrasonic resonance flaw detector thickness guages are manufactured. In Table 5 are given basic parameters of resonance flaw detector thickness guages of domestic and foreign types. One of the best developed foreign instruments is the Vidigage (Fig. 139) made by Branson (United States).

Table 5. Basic Parameters of Resonance Flaw Detector Thickness Gauges

Name of instrument	Producer (developer)	Year of development	Basic technical characteristics	Note
		USA		
Sonigage	General Motors (Erwin and Rassweiler)	1947	Range: 0.75-1.5 1.5-3.0-6.0 MHz. Oscilloscopic indicator. Rotation of capacitor axis by small motor	
Audigage	Branson	1948	Range: 1.4-2.8 MHz; indicator — telephone receiver, rotation of capacitor axis manual	
Reflectogage	Branson (Kerlin)	1948	Range: 0.4-0.8; 1-2; 2.5-5 MHz. Oscilloscopic indicator, mechanical synchronization of scan	
Reflectogage	Sperry	1948	Analogous to pt. 1	
Vidigage-14	Branson	1955	Magnetic modulator, changeable outlying generator unit, length of cable 300 m, screen 260 × 150 mm, weight 27 kilograms	Used by Harris for work immersion method. Measurement error 1-2%
Vidigage-21	Branson	1955	The same as in pt. 5, but screen 400 × 240 mm, weight 63 kilograms	
Sonizon	Magnaflux	1959	Analogous to pt. 1; range 0.25-9 MHz, direct reading of thickness (auxiliary head with key)	

Table 5. Basic Parameters of Resonance Flaw Detector Thickness Gauges (cont'd)

Name of instrument	Producer (developer)	Year of development	Basic technical characteristics	Note
		USA		
Sonizon-200	Magnaflux	1959	Portable instrument, weight 7 kg, battery fed, neon indicator, 3 range	Limits of measurement 0.6-15 mm
Audigage	Branson	1958	Compact model on transistors, weight with battery 2.2 kg	Limits of measurement 2.2-125 mm, error ≤3-5%
Audigage (rail)	Branson (Block)	1952	Range 3-3.3 MHz. Rotation of capacitor axis by small motor, indicator — telephone receiver and pointer-type device	
		USSR		
URD-3	SNKh LSSR (Institute)	1951	Range 3-[illegible] MHz, rotation of capacitor axis by small motor, oscilloscopic indicator	
V4-8R	SNKh LSSR (Institute)	1954	Range 3-6 MHz magnetic modulator, oscilloscopic indicator, weight 22 kg, electrical synchronization	Limits of measurement 0.8-15 mm, error ≤1.5%
UZT-R	TsNIITMASh	1955	Range 2.5-8 MHz, magnetic modulator, oscilloscopic indicator	Error ≤1.5%
URT-6[1]	TsNIITMASh	1960	Range 3-9 MHz, magnetic modulator, oscilloscopic indicator, weight 12 kg	Limits of measurement 0.35-50 mm, error 2%
TUK-4V	3rd Precision Electrical Instruments Plant (VNIINK)	1964	Range 0.6-1.6, 2.8-5.5, 4.8-10.8 MHz, magnetic modulator, oscilloscopic indicator, system of direct reading. Weight 22 kg	Limits of measure- 0.3-45 mm, error 0.5% + 0.02 mm
		England		
Type 1101	Dawe Instruments	1958	Analogous to pt. 2	
Ultrasonic thickness guage	Dawe Instruments	1958	Rotation of capacitor axis manual, pointer-type indicator, head on barium titanate, length of cable 15 m	

Table 5. Basic Parameters of Resonance Flaw Detector Thickness Gauges (cont'd)

Name of instrument	Producer (developer)	Year of development	Basic technical characteristics	Note
		England		
Visigauge	Dawe Instruments Ltd	1958	Analogous to pt. 5	Manufactured by license of Branson firm
		France		
Aerosonic	Realisation Ultrasonic	1960	Rotation of capacitor axis manual, pointer-type indicator	
Sonirail	Realisation Ultrasonic	1960	Analogous to pt. 10	
		Japan		
CM-1	Mitsubishi	1958	The same	

[1]Manufactured by the "Precision Electrical Instruments Plant" under the brand TUK-3.

Two models of the instrument are produced, differing by the cathode ray tubes employed. The "small" model (Vidigage-14) has a tube with a screen 260 × 150 mm, and the large (Vidigage-21) — 400 × 240 mm, with weights of 27 and 63 kg correspondingly. Such a large scale when glow of tube is very bright permits an easy reading from a great distance. The Vidigages differ from other analogous instruments first of all because cathode ray tubes have magnetic deflection.

In this instrument for the first time the system of frequency modulation analogous to the system of the V4-8R is used abroad. The frequency modulated generator is in the form of a detachable assembly and permits working on any frequencies within the limits 0.75-20 MHz depending upon assigned range of measurement of thicknesses.

Capacitance of the high frequency cable connecting generator with searching head affects frequency of generator, therefore the generator assembly can be removed from the instrument together with the searching head. In this case it can be connected with the instrument by a multiple supply cable whose length can reach 300 m. Sensitivity of instrument is calculated so that resonance peaks have a height allowing reading with respect to several overlapping scales superimposed on a transparent plate adjacent to the screen.

These scales are interchangeable and are designated by colored code just as

the corresponding heads. When the instrument is carefully tuned according to the standard samples directly before measurement the thickness reading can be made with very high accuracy. In other cases error does not exceed 1 and 2% — for models 21 and 14 correspondingly.

The English firm Dawes Instruments Ltd. under license by the Branson firm has organized production of the Vidigage, calling it the Visigauge.

With the help of these instruments it is possible to solve a great number of pressing problems in the national economy. The resonance method is widely applied in the USSR and abroad for control of a large number of important articles in conditions of their production and exploitation, where in such cases other methods are inconvenient, difficult, or impossible.

Practical experience with the resonance method shows, however, that in conditions of control of big articles, when the number of measurements is sufficiently great instruments must be not only high precision but also highly productive.

These requirements necessitate a system of direct reading of thicknesses without calculations on a circular slide rule, plane table, or graph, and also a system of automatic signalling working when the instrument shows a thickness going beyond the limits of the fixed allowance, and a system of recording readings allowing an objective document indicating results of control.

Systems of direct reading have been developed in recent years in the USSR by Yu. V. Lange and G. V. Prorokov [18]. They proposed the methods considered below in detail, allowing a solution of this problem and a direct scale reading graduated in thicknesses.

Both these methods are based on comparison of natural frequencies of article with resonance frequencies of standard measuring systems, but are distinguished by fulfillment of the latter.

In the method of Yu. V. Lange the standard system is, similarly to the measured article, a system with distributed constants in the form of an ultrasonic measuring line of variable length.

The schematic diagram of such a device is given in Fig. 140. To ultrasonic resonance flaw detector thickness gauge 1, besides basic piezoconverter 2 radiating UZK into article 3, through adjustable capacitor 4 is connected auxiliary piezoconverter 5, loaded on measuring ultrasonic line 6 of known (standard) thickness.

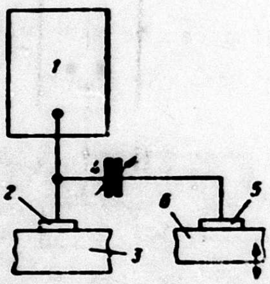

Fig. 140. Schematic diagram of device for direct reading of thickness with an ultrasonic measuring line.

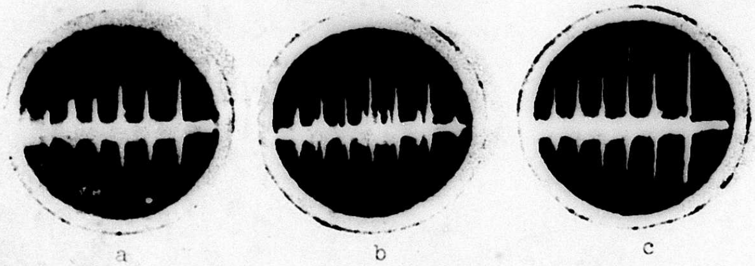

Fig. 141. Image on screen of resonance flaw detector thickness guage during work with reading device.

In this case on screen of instrument will be observed two independent systems of peaks, one — the measured (Fig. 141a), and the other — the standard thickness (Fig. 141b).

Changing the standard thickness it is possible to reach a coincidence of these two systems of peaks, which will occur when resonance frequencies of article and standard coincide. At the time of coincidence of frequencies amplitudes of peaks sharply increase (Fig. 141c).

With such a method of reading the measurement of thickness reduces to adjustment of length of measuring line to coincidence of two systems of peaks on the instrument screen, while the thickness being measured is read directly on the scale connected with the measuring line.

Variable capacitor 4 serves for selection of optimum connection of piezoelectric pickup 5 with generator.

The most simple and compact structural solution of the ultrasonic measuring line — is the liquid system with a mobile reflector in it. However certain structural difficulties are met. The basic ones are: necessity of minute shifts of the reflector and guarantee of boundary conditions of reflection analogous to conditions of reflection of UZK in article.

Necessity of minute shifts of reflector is because rate of propagation of UZK in liquid is small as compared to rate of propagation in metals. Consequently for resonances on the same frequencies (we consider boundary conditions as identical) it is necessary to observe the relationship:

$$\frac{c_1}{d_1} = \frac{c_2}{d_2},$$

where c_1 and c_2 — rates of propagation of ultrasonic oscillations in the metal of articles and in the liquid of the measuring line, d_1 and d_2 — lengths of article and line.

Rate c_2 (in liquid) is approximately 4 times less than rate c_1 (in metal), therefore thickness of line and its change must be four times less than thickness of article.

Thus, upon change of thickness of steel sample by 0.1 mm, to combine the peaks the reflector must move 0.025 mm. Such a relation of changes of thicknesses cannot fail to be reflected on accuracy.

Necessity of creation of a reflector having boundary conditions identical to boundary conditions of the article is because if UZK fall on the interface of two media on the side of the medium with larger wave impedance (for instance on the side of metal on the metal — air interface) reflection occurs with phase shift of 180° (with loss of half-wave); if however UZK fall from a medium with smaller wave impedance (for instance, from liquid on liquid — metal interface) a phase shift is not observed. Consequently, conditions for appearance of resonance in both cases are different and complete combination of peak systems is impossible. Therefore the measuring ultrasonic line turned out to be necessarily made from metal.

The reading device was made in the form of an attachment to the V4-8R. The measuring line was a steel circular wedge about 200 mm in diameter with angle of ascent $\alpha = 32'$.

The measuring wedge shifts relatively to the quartz piezoconverter so that thickness of measuring line under it can change. To create a good and stable acoustic contact between piezoconverter and wedge, the wedge is dipped into transformer oil. Scale of thicknesses, connected with wedge, is on upper cover where reading is made with a motionless sight for which in housing of attachment is a special window. Attachment is connected with flaw detector thickness gauge with a special T-junction. For selection of the optimum connection of the measuring line with the output circuit of the instrument generator in the attachment there is a variable capacitor whose capacitance is regulated by a special handle. To change thicknesses the operator rotates the circular wedge (left handle) until peaks from measuring device coincide with peaks of article on screen of instrument. The measured thickness is counted along a scale graduated in millimeters.

The reading device is conveniently calibrated with respect to measuring samples,

while if rate of propagation of UZK in controlled article differs from rate in these samples, into the reading should be introduced a corresponding correction.[1]

In the reading device of G. V. Prorokov the standard measuring system consists of electrical circuits connected with the circuit of the self-excited oscillator of the flaw detector thickness gauge.

Use of an electrical circuit for measurement of thicknesses in work by the ultrasonic resonance method is based on the fact that such a circuit at the time of resonance renders on the self-excited oscillator the same action as the resonating article, and consequently leads to appearance on the instrument screen of the same peaks as the article during resonance.

A single measuring circuit was first applied in a flaw detector thickness gauge of the TsNIITMASh [188]. Thickness is measured very simply: it is necessary to make two scale readings of the scale connected with axis of variable capacitor of measuring circuit. Readings are taken when mobile peak (moving with respect to the scanning as circuit tuning changes) match consecutively two harmonics of the article. Readings are converted into thickness using graphs, analogously to the method used in the flaw detectors URD-3 and V4-8R. Thus, this method does not involve direct reading of thicknesses.

The problem of direct reading using circuits is solved by creating from several circuits a system which in resonances properties approaches a system with distributed constants.

Theoretically, for full coincidence of natural frequencies of systems with distributed constants with resonance frequencies of a certain standard system the latter also should have parameters. However, for practical purposes this is not required since due to the limited frequency range of the flaw detector the article resonates only on a few harmonics and, besides, it is practically possibly to measure when not all but only part of the harmonics of articles match frequencies of the standard system. Thus the standard measuring system can be from several circuits with lumped parameters. If the number of these circuits is two and the capacitance of the variables capacitors at identical angles of rotation are equal, resonance

[1]A system of direct reading analogous to that developed by Yu. V. Lange, but significantly more complicated (it includes a high-speed electronic comparator, switched into the primary and auxillary converter), was used in the resonance thickness guage Sonizon (Magnaflux, USA).

frequencies of circuits will be expressed so:

$$f_1 = \frac{1}{2\pi\sqrt{L_1C}};\ f_2 = \frac{1}{2\pi\sqrt{L_2C}}.$$

where C — capacitance; L_1 and L_2 inductances of first and second circuits correspondingly.

In formula (48), connecting thickness of article with resonance frequencies we place values of resonance frequencies, setting $f_1 = f_n$ and $f_2 = f_{n+m}$.

After simple transformations we obtain

$$d = \frac{\pi c\sqrt{L_1L_2}}{\sqrt{L_2}-\sqrt{L_1}}\, m\sqrt{C}. \tag{53}$$

From this expression it follows that for the considered case thickness of article d depends on capacitance and difference of numbers of harmonics. From this follows the possibility of scale calibration of the block of variable capacitors of circuits directly in values of thickness.

For simple measurements when working on harmonics on the instrument screen it is necessary to have always two peaks from the measured circuits. It is possible to show that when deviation of frequency is two (accepted in serial flaw detector thickness gauges) to execute the given condition the number of measuring circuits should be not less than three. A diagram of a reading device in the form of an attachment to a serial flaw detector thickness gauge is given in Fig. 142.

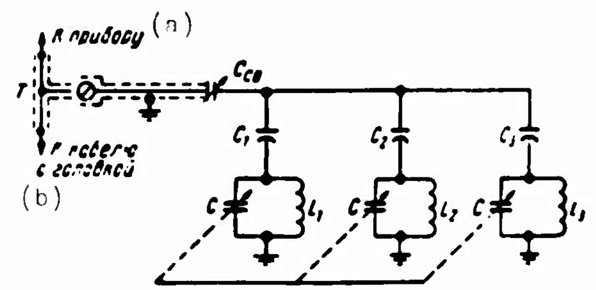

Fig. 142. Schematic diagram of a device with measuring circuits for direct reading of thickness.
KEY: (a) to instrument; (b) to cable with head.

The attachment is joined to the flaw detector with the help of a special T-junction (Fig. 143). Tuning of such an attachment can be done either with radiomeasuring instruments or by calibrated samples.

Work with an attachment is conducted just as with a reading device with an ultrasonic measuring line. The reading is made when frequencies of measuring circuits coincide with two (or three) harmonics of the article according to one of the scales calibrated directly in thicknesses. The scale is chosen depending upon quantity of harmonics of article included between combined peaks. Scale construction provides

measurement of thicknesses of an article from materials with a different value of c. As was shown, exploitation in industrial conditions of an experimental lot of devices for direct reading, both systems are fully reliable and noticeably accelerate measurements.

An example can be the hollow part which was fitted, taking the metal from the surface. In order not to remove too much metal the wall thickness of this part is measured in many points before treatment. Prior to application of the attachment with direct reading measurement of one such part required ~16 h; after introduction of attachments duration of measurements was reduced to 4 h.

Besides evident advantages of direct reading from the point of view of simplicity in exploitation and essential acceleration of measurements there are advantages with respect to accuracy of measurements. The last one is connected with the fact that the measuring system possesses high stability, while properties of this system do not depend on voltage of the supply network, parameters of the cathode ray tube, and other factors influencing accuracy of the usual flaw detector thickness gauge. If the quality of all elements of the arrangement constituting the oscillatory systems and also the controlled article itself is sufficiently high, thanks to the sharpness of resonances in the article and in the measuring device accuracy of combination of the two systems of peaks on the instrument screen is very high which also promotes a decrease of measurement error. Practically error in direct reading is twice less than in measurements by serial instruments using calculation attachments.

Comparing the above two devices, it is possible to see that a measuring system in the form of an ultrasonic line has the advantage over a system with circuits of greater stability and greater number of combined peaks, which excludes subjective errors during the measurement of articles with large thicknesses. However a system with circuits possesses greater compactness, smaller weight and greater simplicity in manufacture than an ultrasonic measuring line possessing almost the same accuracy.

Obviously devices for direct reading of thicknesses in the form of attachments to a flaw detector are not mandatory and on the basis of the presented methods obtaining a direct reading of thicknesses it is advisable to create a flaw detector thickness gauge including one of the described devices. Such an instrument, the [TUK-4V] (ТУК-4В), has been developed by the VNIINK and is ready for serial manufacture. In this instrument a system of peaks corresponding to harmonics of a

special measuring generator is used for reading thickness. It is possible to consider that the TUK-4V will be considerably more convenient in exploitation and more reliable in operation than the serial instruments which are being used.

In foreign models of resonance instruments with automatic frequency modulation, systems of direct reading analogous to those described are not applied. Thicknesses are counted along scales placed on the screen of the cathode ray tube. To increase accuracy of reading tubes with a large diameter of screen are used, which essentially increases weight and dimensions of equipment as may be seen in the example of the Vidigage.

So that with the help of this instrument it was possible to obtain a direct reading of thickness of the measured article on the fundamental frequency, at every measurement it is necessary to select a frequency range in which the article will resonate on the fundamental frequency, which is inconvenient and lowers productivity of control.

A deficiency of the considered method of reading is also inconvenience of control of articles from materials with different rates of propagation of elastic oscillations. Upon transition from one material to another it is necessary to use conversion factors or to change the scale fixed before the screen. Therefore the instrument is given several scales graduated for materials with defined speeds of propagation of ultrasonic oscillations.

Regarding automation of the work of a resonance flaw detector thickness gauge and recording of its readings, such systems as yet are only in the developmental stage. However paths in realization of similar devices are already sufficiently clear.

One of the basic conditions in creating a reliable automatic device is constancy of acoustic contact. Therefore the most promising for automation is the immersion variant of the resonance method.

Automation of a resonance flaw detector thickness gauge is possible by connecting to it a frequency selector, making it possible to note the appearance of a resonance peak in the interval between assigned values of frequency. These values are established, depending upon conditions of control and are observed on the instrument screen in the form of moving electron marks ("official peaks") whose position on the time axis can be changed.

The resonance peak appearing between these marks activates the relay

controlling the servomechanism, giving a sound or light signal or putting the controlled article into the corresponding section. Such a system is simplest to apply in instruments working on fundamental frequency and controlling a narrow range of thicknesses.

Instrument readings can be recorded by different methods. It is possible, for instance, to record the difference of frequencies between first resonance peak and beginning of the scan; it is possible to record all resonance peaks simultaneously, or to record differences of frequencies between one of the adjustable electron marks of the frequency selector and the resonance peak. The frequency selector designed for work with a recorder produces a voltage proportional to the difference of frequencies between resonance peak and electron mark. Inasmuch as this voltage is a function of the measured thickness, it can to be used for the motion of the stylus of a potentiometric recorder, and thus very minute changes of thickness can be recorded. An automatic machine with a recorder of such type is manufactured as an attachment to the Vidigage.

Improvement of equipment in the shown directions and organization of production of resonance flaw detector thickness gauges of different types with "manual" and automatic change of frequency, with different indicators, on different frequency ranges, with devices for direct reading, with automatic signalling apparatuses and recorders, with different searching heads — will allow considerable expansion of application of the resonance method for problems having great national economic value.

V

ACOUSTIC METHODS (IMPEDANCE AND METHOD OF FREE OSCILLATIONS)

1. Physical Bases of Impedance Method, Equipment and Method of Control

The impedance method was developed in the USSR in 1958 by Yu. V. Lange [189][1] in connection with necessity of solving new problems appearing as a result of wide introduction of constructions from laminar elements in aviation and rocket technology. Laminar elements are obtained by gluing sheets, plates, and fillers from different very heterogeneous metallic and nonmetallic materials.

The distinction of physical properties of these materials and also the sharp distinction of these properties from properties of the applied glues creates considerable difficulties in creation of reliable methods of the defectoscopy of glue compounds, completely excluding possibility of using the majority of known methods of nondestructive control.

The basic direction in the development of methods of controlling glue componds in USSR and abroad is the use of elastic oscillations. The use of the sound shadow and resonance methods and also the impulse echo method permits a partial solution of the problem; however these methods are not all-purpose and in a large number of cases cannot be used.

In this meaning the impedance method possesses very interesting possibilities which make it possible to consider it one of the most promising and all-purpose means of the defectoscopy of glue bonding.

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[1] Yu. V. Lange and A. V. Rimskiy-Korsakov. Author's certificate No. 126653, USSR, 1958.

The method is based on using the dependence of full mechanical resistance (impedance) of the controlled article on the quality of the bonding of separate elements.

Change of input impedance of system (controlled article) can be revealed by different methods, for instance by change of amplitude or phase of reaction force influencing the pickup, exciting in the article elastic — mainly flexural oscillations (proposed by Yu. V. Lange) or by change of natural frequency of pickup (proposed by A. A. Tukkayev).

In the instrument developed by Yu. V. Lange[1] the first method is used, due to which this variant of the impedance method came to be called the "reaction method."

The pickup in this instrument is a rod accomplishing longitudinal oscillations. If this rod (Fig. 144) contacts a section of sheathing rigidly glued with an internal sheet they oscillate as a single unit and mechanical resistance of article to rod is determined by rigidity of the whole. Force of reaction F_p of the article to the rod becomes large.

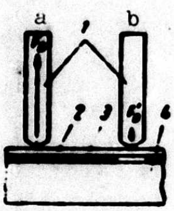

Fig. 144. Quality control of bonding by impedance method on sections with good bonding a and in an unglued zone b [189]: 1 — pickup; 2 — external sheet (sheathing); 3 — layer of glue; 4 — internal sheet (sublayer).

If, however, this rod is above the defective zone, the unglued section of sheathing oscillates as a disk pressed on the contour independently of the whole. Inasmuch as rigidity of sheathing is considerably less than rigidity of the whole, force of reaction F_p' sharply decreases.

A diagram of the pickup developed for the impedance acoustic flaw detector [IAD-2] (ИАД-2) is shown in Fig. 145. It is composed of rod 1 of plastic shaped like the frustum of a cone. To the major axis of this cone is glued piezoelement 2 (plate of barium titanate), excited from the audio frequency generator and radiating elastic oscillations in rod. Steel cylinder 3 glued to the other surface of piezoelement plays the role of a reflecting mass and is used to increase intensity of radiation of piezoelement into rod.

To smaller base of rod is glued second piezoelement 4 from barium titanate, acting as a dynamometer and intended for measurement of variable component of force of reaction of article to pickup, caused by oscillations of rod of pickup.

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[1]A. P. Chernyy designed the first model of the ("glue bonding tester"). A. D. Gol'den and S. L. Yakovis designed the industrial models of the IAD-1 and IAD-2, put into serial production by the "Precision Electrical Instruments Plant."

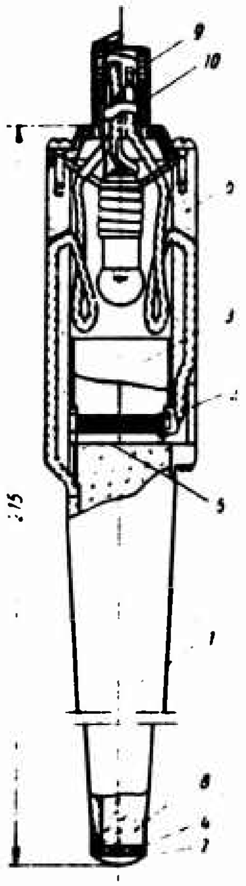

Fig. 145. Diagram of pickup (IAD-2) for control by impedance method [190]: 1 — sound-conducting rod; 2 — radiating piezoelement; 3 — reflecting mass; 4 — dynamometric piezoelement; 5 — screen; 6 — body; 7 — contact tip; 8 — brass ring; 9 — sheathed wire; 10 — safety steel spiral.

Stress on piezoelement is proportional to its deformation, therefore when pickup is not pressed to controlled article the rod accomplishes longitudinal oscillations and the receiving piezoelement oscillates together with the rod as a unit, displaced relatively to its own initial position but not being deformed and not developing any stress on facings (reaction force of ambient air may be disregarded). If lower end of pickup is pressed to article, force of reaction of article causes deformation of piezoelement which feeds a stress proportional to this force to the measuring part of the instrument — the sensitive amplifier having on the output a pointer-type indicator and relay activated when output voltage becomes lower than the fixed level of the signal tube in the upper part of the pickup. Contact tip 7 is made of a magnesium alloy, which is advisable for lowering inertial resistance. To increase wear resistance in the tip is a "mushroom" from hardened steels. The dynamometric piezoelement is protected from electrical interferences and mechanical damage by brass ring 8.

The IAD-2, shown in Fig. 146, is designed for work in the range of 1.0-6.5 kHz where optimum frequency is selected depending upon parameters of article.

The control technique with the IAD-2 is very simple: the operator places the pickup on the controlled article along the normal to its surface, and slightly pressing brings the end of the pickup along this surface, watching the readings of the indicator (pointer-type device and signal tube).

Laboratory and industrial tests of the impedance method showed that this method successfully controls quality of glue bondings in three-ply thin metallic sheathing, for instance of steel or duralumin 0.4-0.8 mm thick glued to a thicker metallic sheet or with a honeycomb (or nonmetallic: fiberglass, laminate, delta wood, foam, plastic) filler.

If, however, sheathing is of materials with low elastic properties (low high quality) such as, rubber, foam, plastics, or the whole article is bonded from such materials that the impedance method does not permit detecting a disturbance of

bonding in these articles.

The impedance method with equal success may be used to control both bonded and soldered constructions, inasmuch as a film of solder or glue has no considerable influence on general rigidity.

Somewhat unique are conditions of quality control by impedance method for bonding of sheet-type sheathing with honeycomb filler, inasmuch as input impedance of article is unequal in different points of sheathing: it is largely on edges of honeycomb cells and less in their center. Difference in values of input impedance grows with increase of dimension of cells and fluctuations of indicator readings observed when article is scanned by lines create a background disturbing to control. The background is small for dimensions of cells up to 6 mm, however at further increase of these dimensions it becomes commensurable with level of signal corresponding to defective section, which hampers control or makes it impossible.

Inasmuch as for installation of pickup practically a point section of surface is required, the impedance method permits control of an article with c siderable curvature of surface (up to a radius of curvature of 6-8 mm) and also control for the actual edge of the bonded article, i.e., in the most dangerous zones (here sheathing can lag in exploitation under sign alternating loads). Minimum area of revealed defect is near 15 mm^2.

For control of articles by impedance method bilateral access is not needed, it is not necessary to dip article in bath with immersion liquid or to apply contact lubricant on surface of article, inasmuch as elastic low frequency oscillations are sufficiently effectively introduced into the article through dry contact.

The impedance method naturally can be used to control not only a bonding created by soldering or gluing but also diffusion bondings, for instance, plated sheets and rods.

It is possible to affirm that the field of application of the impedance method is very wide.

Control by impedance method can be automated; scanning of surface of article is done with a special mechanism in the head of which is a pickup, and the indicator readings are recorded on electrothermal paper.

A sample of the recording of readings during quality control of bonding of sheet-type sheathing with honeycomb filler obtained with the automatic recording attachment developed by Yu. V. Lange is shown in Fig. 147. The hundreds of walls

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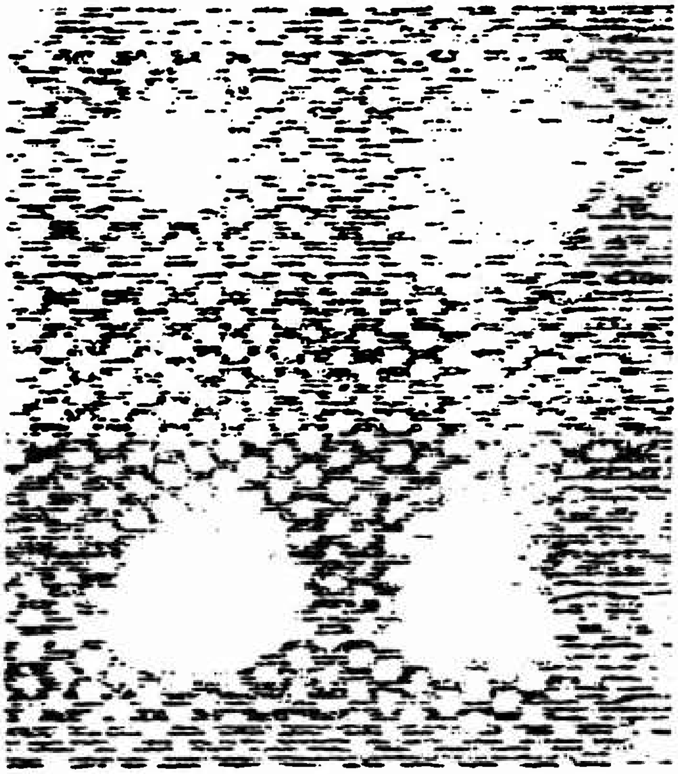

Fig. 147. Sample of readings of the IAD-2 in the quality control of bonding of sheet-type sheathing with honeycomb filler.

and contours of zone of disturbance of cohesion are distinct, which permits reliable control of article with such cellular dimensions when manual control is impossible due to the previously mentioned background.

At present the impedance method is so highly recommended that it can be recommended for wide application in cases requiring one hundred percent reliable control of constructions on a base of glued and soldered bonding. However, production and exploitation conditions of such constructions advance ever new problems which the impedance method does not solve. Such problems include, for instance, determination of strength of bonding when there is no separation, i.e., when internal surface of sheathing is not separated from sublayer by an air filled gap.

The solution of this very complicated problem in principle is possible on the basis of using "normal" waves.

2. Physical Bases of the Method of Free Oscillations, Equipment, and Method of Control

The method of free oscillations is probably the oldest of all methods of defectoscopy using elastic oscillations. This method has long been used, for

instance, by railroad inspectors to detect axle cracks in locomotives and railroad cars. Using a small hammer and striking along the axle, the inspector judges "purity" of ringing and determines presence of cracks. The quality of glass and crystal articles is checked similarly. Tapping along the edge of a glass article, it is possible (also by purity of ringing) to distinguish a defective article from a suitable one.

The method of free oscillations in such very primitive form is of course very subjective, however its sensitivity is rather high and an experienced controller possessing a musical ear can sort similar articles sufficiently accurately.

Physical bases of the method of free oscillations are the following: if a solid body (the mechanical oscillatory system being characterized by defined parameters — mass, flexibility, and mechanical resistance) is excited by a sharp blow from without, in the system will appear free or natural damped oscillations.

The initial amplitude of these oscillations is determined by energy imparted to the system from without upon impact. After action of external force ceases the system is left to itself, therefore the period of oscillations of the system, and also the logarithmic damping decrement are determined by parameters of the actual system and do not depend on energy imparted to the system from without. Thus for the simplest oscillatory lumped system (load suspended on spring) frequency of natural oscillations is

$$f_0 = \frac{1}{2\pi\sqrt{mC_M - \left(\frac{2m}{R_M}\right)^2}} \text{ Hz}, \tag{54}$$

where m — mass of system (kg); C_M — flexibility of system (s^2/kg); R_M — mechanical resistance of system (kg/s). Logarithmic damping decrement θ — the most important characteristic of oscillatory processes — is determined by the expression

$$\theta = \pi \frac{R_M}{\sqrt{\frac{m}{C_M}}} = \frac{\pi}{Q},$$

where Q — high quality of oscillatory system.

With assigned geometric dimensions and form of article and physical homogeneity of material from which it is prepared, frequency of its natural oscillations is a fully defined magnitude. However, if in material of article is a heterogeneity

(for example, a stratification), one basic parameter of the oscillatory system changes (flexibility), and if this heterogeneity has considerable volume (for instance, a pit), then mass changes noticeably, which should lead to a change of frequency of natural oscillations and a logarithmic damping decrement.

The given reasoning pertains to an oscillatory lumped system. A solid body is a distributed system, where this distribution can be uniform or nonuniform. Nonuniform distribution of parameters appears especially sharply in laminar constructions from heterogeneous materials of joined over the entire surface (for instance with glue). In this case the phenomenon is somewhat complicated — upon excitation of such a system oscillations on several frequencies can appear within limits of a certain spectrum of frequencies.

Change of homogeneity of material of system causes relative change of amplitude of specific components of this spectrum and of the logarithmic damping decrement of these components. This may be clearly seen from experiments carried out by Yu. V. Lange [190]. On a special installation were obtained oscillograms of free oscillations excited in standard conditions by a freely falling steel ball in a special model consisting of a duralumin plate 0.8 mm thick glued to a massive bar also of duralumin. In the model zones of no bonding of different dimensions were artificially created. The ball struck the model on the side of a thin sheet. As oscillogram time marks 10 kHz sinusoidal oscillations were used, which were conspicuous simultaneously with investigated free oscillations on the screen of a double trace oscilloscope. Analysis of obtained oscillograms shows that character of sound pulses in places with defective bonding essentially differs from pulses corresponding to healthy sections of the model. This distinction concerns first of all spectral composition, which changes the sharpest — a place of no bonding leads to appearance of high frequency spectral components.

Therefore in order to liquidate the basic deficiency of the method of free oscillations, in its simplest form — subjectivity of appraisal of readings — it is necessary to provide in the instrument a corresponding device for analysis of frequency spectrum, excluding necessity of this analysis by ear.

One attempt at a solution to this problem is the instrument whose diagram is shown in Fig. 148. The striker of the pickup, fastened on the armature of electromagnet 2, strikes the surface of controlled article 1 with the frequency of the alternating current feeding the electromagnet, exciting in the article free

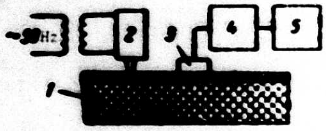

Fig. 148. Block diagram of instrument for quality control of bonding according to amplitude of free oscillations excited by a striker [190]: 1 – controlled article; 2 – electromagnet; 3 – microphone; 4 – amplifier; 5 – indicator.

oscillations. Microphone 3, fixed on surface of article a certain distance from the pickup, picks up these oscillations and transmits electrical signals to amplifier 4 on the output of which is switched in a relay controlling lighting of signal tubes of indicator 5. If pickup is on the section above a zone of no bonding, amplitude of oscillations excited in article drops, signal on output of amplifier decreases, the relay is activated and lights the corresponding signal tube.

With this instrument it is possible to reveal defects bonding of thin (0.8 mm) sheet-type sheathing of duralumin bonded with foam plastic. However, an attempt to detect defects in bonding of two metallic elements (sheathing 0.8 mm thick and internal sheet 4 mm thick) did not give a positive result.

Evaluating the work of such an instrument, it is possible to say that it makes control somewhat more convenient; the basic goal – exclusion of subjectivity – is not attained inasmuch as the instrument does not provide an analysis of the frequency spectrum of oscillations.

In an installation for testing articles for homogeneity by the method of free oscillations with application of analysis of frequency spectrum the striker hits on the surface of the controlled article and excites in it free oscillations. The microphone fixed on the surface of the article a certain distance from the striker picks up elastic oscillations, converts them into electrical and moves them to the amplifier, from there – to the frequency analyzer and finally to the vacuum tube voltmeter. If an article from a material with large damping of [UZK] (УЗК) is investigated, the striker can excite the system not by a single blow, but periodically, for instance with a frequency of 50 Hz, inasmuch as oscillations appearing as a result of the blow completely fade before the following blow is made. Under periodic excitation it is convenient to conduct an observation with a cathode ray oscilloscope.

Method and equipment for detection of internal defects in massive articles from materials with large damping of elastic oscillations, and in particular for determination of stratifications and defects of bonding in laminar materials at a

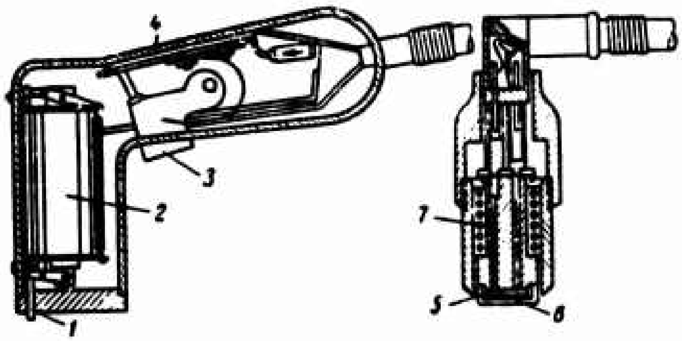

Fig. 149. Diagram of heads for the ChIKP.

depth of up to several centimeters has been developed in USSR.[1] A diagram of vibrator and receiver of the [ChIKP] (ЧИКП) ("frequency tester of bonding quality") is shown in Fig. 149. Striker 1 of the vibrator is activated by electromagnet 2, switched in by starting push button 3 located in handle of vibrator 4. In the receiver is piezoelectric plate 5, protected from damage by header 6 and pressed to surface of controlled article with a force determined by the spring force of spring 7. The receiver converts the whole spectrum of elastic oscillations into electrical, which after amplification go to a filter passing the oscillations of only those frequencies which characterize the frequency spectrum of a "defective" section. After the filter oscillations of these "characteristic" frequencies are amplified and go to the vacuum tube voltmeter which measures their amplitude.

The ChIKP has been successfully used under conditions when other methods of control cannot be applied with proper effect, for instance, for quality control of the bonding of materials with high value of attenuation factor of elastic oscillations (textolite, asbestos textolite, plywood) among themselves or with metallic sheathing, and also for detection of continuity disturbances inside any layer of the enumerated nonmetallic materials.

In foreign literature [47] are data about the successful application of the method of free oscillations. There are mentioned two possible methods of excitation of free oscillations (single blow and continuous periodic blows), advantages of the second method are enumerated, and equipment with which this method has very successfully been used in the United States to control abrasive disks for the absence of cracks in them is described [194, 195]. In the control frequency of natural

[1] N. S. Akulov, V. A. Kunavina, V. I. Akimov, B. I. Ol'chev. Author's certificate No. 120361, USSR, 1958.

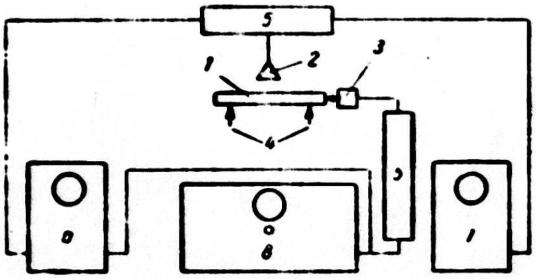

Fig. 150. Block diagram of sound comparator for control of abrasive disks [47]: 1 — sample; 2 — microphone; 3 — pickup; 4 — support; 5 — amplifier; 6 — oscilloscope; 7 — cathode voltmeter; 8 — variable frequency generator.

oscillations of the disk are determined. This frequency is different for a high-quality disk and a disk with a crack, and therefore can serve as a criterion for quality evaluation.

Such a method can be used for reliable control of articles uniform in form and dimensions and made of material sufficiently uniform in its own physical properties. It is clear that multilayer articles obtained by means of bonding separate elements from heterogeneous materials are not suited for control by this method.

The block diagram of an instrument (sound comparator) utilized for control of abrasive disks is shown in Fig. 150.

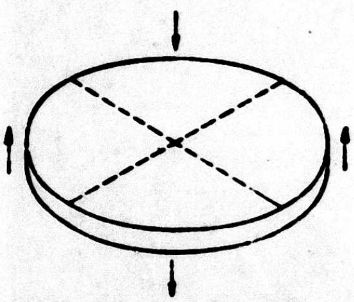

Fig. 151. Diagram of oscillation of an abrasive disk during the control process [47].

The generator of audio frequency, changing in certain limits, feeds voltage to horizontal deflecting plates of the oscilloscope and through the amplifier — to the electromagnetic vibrator. The radiator introduces oscillations through the lateral surface of the controlled disk, as a result of which the disk oscillates according to the diagram on Fig. 151, thus that phases of oscillations of adjacent quadrants always shifts 180°, phases of oscillation of opposite quadrants coincide. Therefore nodes of oscillations of disk are shown by two mutually perpendicular diameters. The disk is on point supports oriented along "nodal" diameters, which permits bringing damping action of supports to a minimum.

A microphone is established near the antinode of disk oscillations and the voltage from it passes through an amplifier containing a vacuum tube voltmeter and

to vertical deflecting plates of the oscilloscope. With change of frequency of generator on the oscilloscope screen different Lissajous figures can be observed corresponding to resonances on natural frequency of oscillations of disk and on its harmonics, and it is possible to measure by voltmeter amplitude of natural frequency and harmonics.

As can be seen from what has been said this method does not provide analysis of frequency spectrum of oscillations of controlled article and control reduces to determination of basic frequency of free oscillations. Such a method is a unique variant of the resonance method, differing from it in that resonance phenomenon are observed in conditions of not forced but free oscillations.

Obviously each variant of the method of free oscillations — developed in the USSR (analysis of frequency spectrum of oscillations) and applied in the USA (determination of natural frequency of oscillations of controlled article) — has its own advantages and disadvantages. These methods, mutually supplementing one another, help to expand the region of effective control of articles of different character.

A recent objective method of free oscillations has great promise; wide industrial tests will promote the clarification of all possibilities of this method.

VI

THE ECHO-METHOD

ULTRASONIC DEFECTOSCOPY

1. Physical Bases of Method

In the echo-method of ultrasonic defectoscopy the same principles are used as in radio- and acoustic location.

In radar equipment a special radiator (directed antenna) sends a narrow beam of electromagnetic oscillations (sounding radio beam) into an investigated air space, "feeling" it in different directions. If the beam meets any heterogeneity able to reflect electromagnetic oscillations (aircraft, ship, clouds, water, etc.) part of the energy of reflected electromagnetic oscillations can be taken by the receiving device located in direct proximity with the radiator or together with it.

If distance between locator and reflector is continuously changed, Doppler effect is observed in change of frequency of reflected electromagnetic oscillations. When sent and reflected oscillations are mixed in the converter, on its output appear beats whose frequency depends on speed of relative displacement of locator and reflector along direction of sounding beam. If, however, frequency of sent oscillations is modulated, frequency of beats appearing when sent oscillations are mixed with reflected will change depending upon time of delay of the latter, which will allow judgment about distance between locator and reflector.

Such systems of radars working in conditions of continuous radiation result in very accurate measurements; however, they have a limited use for distance — they cannot be used for detection of objects a considerable distance away,

since a weak reflected signal cannot be covered against the background much more powerful transmitted signa.

More all-purpose are locators working in conditions of pulse radiation. Electromagnetic oscillations are sent, moreover, in the form of pulses of minute duration (order of a microsecond) divided by pauses whose duration is of the order of a millisecond. Reflected oscillations are received during pauses without any interferences on the part of the radiator, which during pauses without any interferences on the part of the radiator, which during this time does not work. With respect to time of delay of echo relative to a transmitted signal one can determine distance between locator and revealed object, and with respect to amplitude of echo it is possible to judge dimensions of reflecting surface of this object.

Sensitivity of such a locator is very high, inasmuch as echos of even insignificant amplitude can be received by a sensitive receiver in the absence of interferences from the generator. However, if distance to reflecting surface is small and echo arrives before termination of the transmitted signal, such a echo against the background of a considerably more powerful transmitted pulse cannot be received, and consequently a object located at such distance is not revealed. Detection is possible only at distances exceeding the so-called "dead band" of the locator, when echo arrives after termination of transmitted pulse. Extent of dead band may be estimated from the expression

$$l_{min} = \frac{c\tau}{2}, \qquad (55)$$

where c — rate of propagation of oscillations; τ — duration of transmitted pulse.

Thus, range of locator is limited by minimum of dead band. Regarding, however, ultimate range of action, it can be sufficiently great, inasmuch as work in pulse conditions permits concentrating huge power in pulse $W_{\text{И}}$ for a small average power of locator W_{O}, determined by product of pulse power by pulse duration (τ) and by frequency of following ($F_{\text{СЛ}}$) (see diagram Fig. 152):

$$W_0 = W_{\text{и}} \cdot \tau \cdot F_{\text{сл}}. \qquad (56)$$

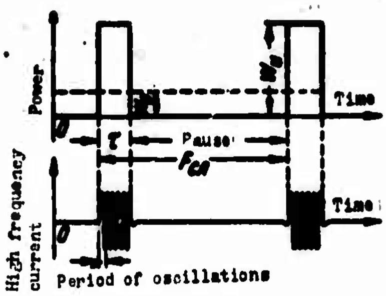

Fig. 152. On the relationship between mean W_0 and pulse $W_И$ power during operation of a pulse generator.

Thus, if power in pulse is 700 kW, pulse duration is 1 μs, and frequency of following of pulses is 300 Hz (such a locator operating at f = 3000 MHz possesses a range near 300 km, and a dead band near 150 m) average power of locator will equal

$$W_0 = 7 \cdot 10^5 \cdot 10^{-6} \cdot 300 \approx 200 \text{ W}.$$

With such relationships the locator can be sufficiently compact, since tubes and other low power parts can be fed a voltage considerably exceeding the specification voltage, which is calculated for continuous operation.

Electromagnetic oscillations are practically completely reflected from the surface of water or a solid possessing electrical conductivity (for instance from the surface of metal). Therefore detection of any objects by radar methods is possible only if between locator and object there are no barriers from water or metal.

In this meaning the acoustic location has indubitable advantages, allowing work in any medium possessing elastic properties — in a gas liquid or solid. However, effectiveness of acoustic location in different media is different due to the difference of the attenuation factor of elastic oscillations.

Inasmuch as for an increase of sensitivity and resolving power, as will be shown later, it is advisable to increase frequency of applied electromagnetic or elastic oscillations, the range of the acoustic (more precisely, ultrasonic) locator in gas, liquid and a solid will be different, and moreover many times smaller than the range of radar using electromagnetic oscillations which propagate great distances in air.

Ultrasonic location in air is found in nature. It is known for instance [196], that a bat is oriented in flight in complete darkness using its own sound apparatus it sends pulses of ultrasonic oscillations at 10-150 kHz and up to 2-3 ms long with a frequency of following of 5-60 Hz. Pulses reflected from obstacles (echos) are sensed by the hearing apparatus of the bat, allowing it to determine direction and to estimate distance to obstacle.

An ultrasonic locator for blind people is based on the same principle. It contains a radiator of ultrasonic oscillations at 18-65 kHz sending short pulses with frequency of following 10 Hz. Echos reflected from obstacles are picked up by a crystal microphone and after amplification by beat receiver go to the headphone. The instrument works in range of distances 1.5-15 m and possesses high sensitivity.

The range of such an instrument [197] is limited by damping of ultrasonic oscillati-- in air, sharply increasing with increase of frequency. Therefore application of oscillations of higher frequency is impossible; lowering of frequency is also unadvisable since it leads to a lowering of sensitivity and resolving power.

Ultrasonic location in water[1] occurs in more profitable conditions: damping of ultrasonic oscillations in water is considerably less than in air. Therefore on the same frequencies it is simple to ensure a sonar range of several kilometers, which permits solving various problems appearing in naval practice — detection of underwater obstacles and measurement of distance to them, measurement of depth of sea, communication between submarines, etc.

Ultrasonic location in water was engendered during the first worls war mainly on the basis of the works of Langevin and Chilowsky[2] and at present is a very well-developed region of technology using special equipment working as a rule in pulse conditions [199].

The echo-method of ultrasonic defectoscopy is ultrasonic location in a solid body, mainly in metal. This method, just as radio location and location in water can be carried out in two variants — on the basis of continuous or pulse radiation.

The echo-method of defectoscopy, based on continuous radiation of ultrasonic oscillations, was proposed in 1941 by S. Ya. Sokolov for determination of the thickness of a hardened layer during surface hardening of massive steel parts. The essence of this method is that (Fig. 153) piezoelectric converter 3 receives from generator 2 high frequency voltage f modulated in defined limits. Modulation

[1]In nature dolphins use ultrasonic location in water.

[2]P. Langevin, N. Chilowsky. French patent No. 503913, 1918.

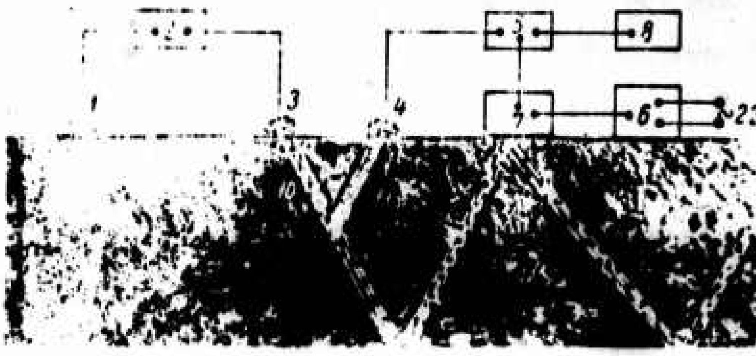

Fig. 153. Determination of thickness of hardened layer according to method of S. Ya. Sokolov: 1 — small motor; 2 — generator with frequency modulation; 3 — piezoelectric converter; 4 — piezoelectric receiver; 5 — amplifier; 6 — stabilizer; 7 — rectifier; 8 — oscilloscope; 9 — hardened layer; 10 — incident beam, 11 — reflected beam.

is carried out by means of changing frequency of circuit of generator, for which the axis of the circuit capacitor revolves with the help of a special small motor 1. Piezoelectric converter 3 transmits into the metal ultrasonic oscillations changing frequency in the form of beam 10. Reaching the boundary of the hardened layer, beam 10 is partially reflected and reflected beam 11 reaches receiving piezoconverter 4. Inasmuch as between generator and receiving device is an electromagnetic bond oscillations of different frequency simultaneously proceed to input of receiver: f and $f + \Delta f$, where Δf — change of frequency of generator during the time of passage of ultrasonic oscillations from radiating piezoconverter 3 to boundary of hardened layer and after reflection from it — to receiving piezoconverter 4. Thus Δf can serve as a measure of thickness of the hardened layer. In the receiving device frequency Δf can be separated, and after corresponding amplification alternating voltage of this frequency can be fed to the oscilloscopic indicator. By image on screen of oscilloscope it is possible to judge Δf, and consequently and thickness of hardened layer.

It is necessary however, to note that to carry out S. Ya. Sokolov's idea there must be a sharp boundary between the surface layer and the base metal. From this point of view measurement of thickness of a hardened layer is the least suitable field of application of this method, inasmuch as transition from structure of hardened layer to the initial occurs smoothly through a series of intermediate

structures. Therefore the method of S. Ya. Sokolov has not been used to measure thickness of a hardened surface layer[1]. Thickness of layers sharply different from the base metal (for instance galvanic plating) are more effectively measured by other methods — magnetic method and method of eddy currents.

In 1934 S. Ya. Sokolov [126][2] proposed a method of detection of defects in a solid body based on registration of change of phase of oscillations attaining a receiving converter located near the opposite edge of the controlled article. The phase of these oscillations will be different in the presence or absence of heterogeneity on the path of the spreading beam. Encountering a defect, whose area obviously should be larger than the cross section of the [UZK] (УЗК) beam, beams go around it, as a result of which time expended on passage of oscillations from radiator to receiving converter will be more than in the absence of a defect. S. Ya. Sokolov did not publish data on this method in practice, however it is possible to affirm that sensitivity of such a method cannot be great, inasmuch as diffractional phenomena on UZK of high frequency is expressed weakly. When using low frequencies a sufficient effect can be obtained and from this point of view the phase method is long-term.

In the proposal of S. Ya. Sokolov are elements indicating that he was very close to creation of pulse echo-method. Thus one of the variant instruments proposed by S. Ya. Sokolov provides registration of the phase change of UZK reflected from the opposite face of the controlled article and reaching the converter together. This converter in turn executes the function of radiator and receiver of UZK, since the generator works only during the positive half-period of modulation voltage. In the course of a negative half-period, the generator serves as a receiver. Frequency of modulated voltage strictly corresponds to thickness of controlled body, which should be known beforehand, therefore when a defect is in the path of a beam, the phase of reflected UZK will differ from the phase in the absence of a defect, which should be marked by the indicator.

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[1]N. N. Yegorov in 1958 described [201] his pulse echo-method of measuring the depth of a hardened layer (with no worse than 90-92% accuracy), based on selective reflection of UZK of defined frequencies from crystallites possessing the greatest elastic anisotropy.

[2]See also S. Ya. Sokolov. Author's certificate of USSR No. 48894, 1934.

To remove reverberational interferences, S. Ya. Sokolov proposed the use pulse radiation for which with help of mechanical-optical system a generator should be switched in on a very short interval of time, and then — when the generator is turned off — at a specific moment the receiver should be switched in. Oscillations "late" due to diffraction of the defect arrive after turning off of receiver and are not recorded. This indicates the presence of a defect.

S. Ya. Sokolov noted in his device an analogy with the sonic depth finder with which, however, it is difficult to agree. In the sonic depth finder to judge sea depth transit time of UZK along a direct line from a radiator mounted in the hull of a ship to the sea bottom and back is measured. If on the path of the beam an obstacle is met which UZK are forced to round, the sonic depth finder will give incorrect readings. In the considered method the phase of reflected UZK can be changed not only in the presence of a defect but also due to a change of thickness of the controlled article.

The method does not provide a registration of UZK reflected from a defect, which is the basis of the pulse echo-method. This problem is solved with the use of equipment analogous to radar. This method, proposed by S. Ya. Sokolov, was developed by him several years prior to the creation of radar systems.

The contemporary pulse echo-method of ultrasonic defectoscopy, based on sending of short pulses of elastic oscillations onto the controlled article and registration of intensity and time of arrival of echos reflected from defects, was proposed in 1942 by Firestone[1]. Since then this method has rapidly developed [203] and now is the most wide-spread of all known methods of ultrasonic defectoscopy.

The pulse echo-method permits solving the following problem of defectoscopy.

1. Detection and determination of coordinates of defects constituting disturbance of continuity (pits, cracks, stratifications, flocks, slag inclusions, friable zones, etc.) and located on the surface or vertually at any depth under the surface of metallic and nonmetallic articles and half-finished products and also in welded and riverted connections.

2. Determination of dimensions of articles and half-finished products of average and large dimensions in places of inaccessible measurement by usual methods.

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[1]F. A. Firestone. American patent No. 228226, 1942.

3. Detection of zones of coarse graining in metallic articles and blanks.

In solving the first two problems reflection of UZK from surface of defect or from surfaces of controlled article is used; the third problem is solved by considerable scattering UZK by crystallites of large dimensions. All these problems are solved with one-sided access to controlled article.

The work of a pulse ultrasonic echo-flaw detector is analogous to the work of hydroacoustic instruments – sonar and hydrosonic depth finder. The radiator sends into the investigated medium short pulses of high-frequency elastic oscillations, separated by relatively prolonged pauses. If on the path of the UZK is an obstacle which it is possible to consider as a discontinuity of acoustic properties of the medium, echos reflected from its surface reach the receiving device near the radiator and are marked by the indicator.

Measuring time from moment of sending the pulse to moment of receiving the echo, it is possible to determine the distance up to the obstruction. Dimensions of the obstruction (the defect) can be judged by the amplitude.

In the pulse echo-flaw detector, a block diagram of which is in Fig. 154 the radiator of UZK pulses is a piezoelectric converter excited by radio pulses of a special generator (exciter). UZK through a film of contact lubricant (in contact variant of method) or through a layer of liquid of considerable thickness (in immersion variant) are introduced into the controlled article. Reflected echos are received by the same (or, more, rarely – separate) piezoconverter, in the form of radio pulses are fed to the input of the receiving-amplifying channel and from the output finally go to the oscilloscope with a driven sweep, started with the help of a special generator simultaneously with radiation of pulse by exciter. During control of articles on screen of indicator marks (peaks) are noticeable, corresponding for the contact variant to moment when pulse (initial signal H) is sent, moment of arrival of echo from opposite edge of controlled article (bottom signal Д by analogy with sonic depth finder) and if a defect is present

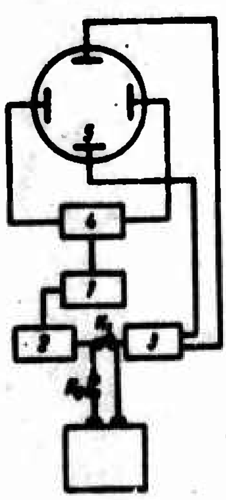
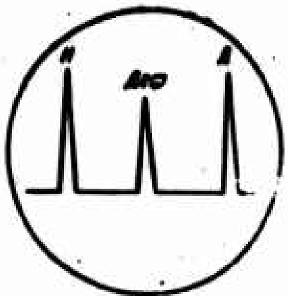
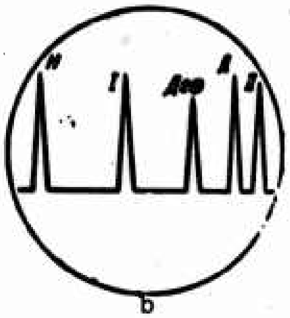


Fig. 154. Block diagram of pulse echo-flaw detector: 1) timer; 2) pulse generator; 5) electron-beam tube; K_1 and K_2 – switches for work to separate and combined converters.



a



b

Fig. 155. Image on screen of echo-flaw detector operating in contact — a and immersion — b variants; I and II first, and correspondingly second, reflection from front edge.

echo from the defect is seen [DEF] ((ДЭФ)), located between initial and bottom at a distance from initial proportional to depth of bedding of defect (Fig. 155a).

During work by immersion variant of the echo-method on screen of indicator after initial signal is seen one more peak corresponding to echo from front edge of controlled article (Fig. 155b).

If structure of controlled section of article is coarse-grained, UZK undergo considerable scattering on boundaries of crystallites and bottom echo is sharply weakened and sometimes even vanishes[1]. In this case a echo from the defect will be observed only for considerable dimensions and shallow bedding of the latter.

Shifting UZK radiator and receiver along surface of article and observing picture on screen of flaw detector, it is possible to carry out reliable control of article against the presence of defects, and to determine their coordinates.

2. Equipment

The first industrial model of a pulse echo-flaw detector was developed in the United States by Firestone and manufactured by the Sperry firm in 1943 under name "Reflectoscope." This instrument (Fig. 156) was very bulky and heavy and inconvenient in the operation due to the great number of adjustable tuning controls; it's picture on the screen was confused (Fig. 157). Nonetheless until the manufacture of improved instruments this flaw detector was used in industry for control of large-scale articles.

In the same 1943 in England the Hughes Firm manufactured the flaw detector "Mark II," built in two units mounted on one another during operation, and also

[1]Weakening of bottom echo is observed also when a defect is met on the path of the UZK. Defect is near front or rear edge of article, the echo from it on the screen will not be seen and amplitude of bottom signal is the only indicator of detection of a defect (this is used in the mirror variant of the shadow method).

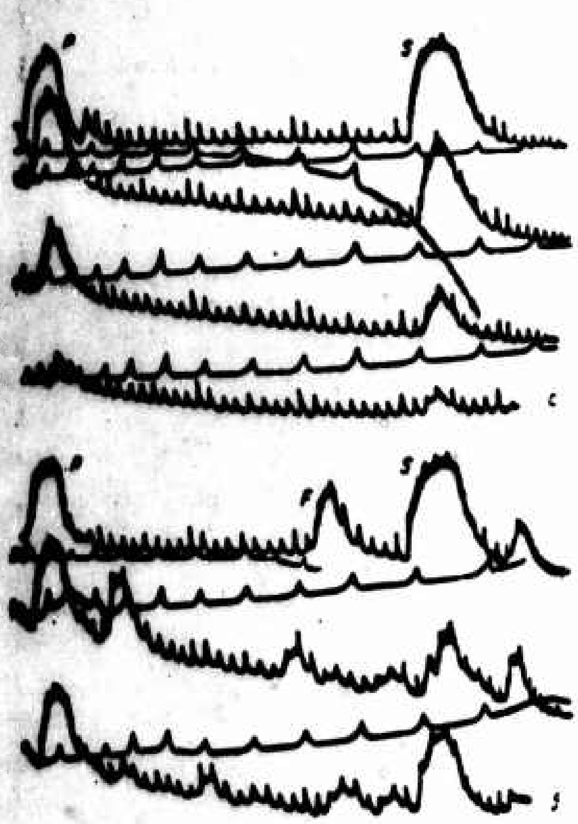


Fig. 157. Image on screen of the "Reflectoscope" in the atsence – a and presence – b of a defect in controlled article: P – sounding signal, S – bottom echo, F – echo from defect.

the more compact "Mark III," made in one unit. These instruments were considerably simpler in control than the Sperry reflectoscope, however they were less sensitivite and did not allow operation of a combined searching head.

In 1948 in the author's group at the Institute begain work on creation of the first Soviet models of pulse echo-flaw detectors of the series [86-IM] (87-ИМ). Then in the laboratory of S. Ya. Sokolov at the Leningrad Electrotechnical Institute flaw detectors of series of the [UZD] (УЗД) are designed. From 1950 work in the region of ultrasonic defectoscopy developed at TsNIITMASh, the TsNIIMPS, the TsNIL Gosgortekhnadzor, NII at the [State Scientific Research Institute of Bridges], where instruments of the UZD and [URD] (УРД) series were created.

At present in the USSR and abroad a great number of types of pulse echo-flaw detectors designed for work in different conditions are being manufactured. Table 6 gives basic characteristics of the most wide-spread Soviet and foreign flaw detectors.

Flaw detectors in the table may be divided into four basic groups:

1) small-size flaw detectors;

2) portable multipurpose flaw detectors;

3) all-purpose mobile flaw detectors;

4) stationary flaw detectors – high productivity, semi-automatic.

Specialized flaw detectors intended for control of specific articles can be made according to a simplified diagram and shaped limiting compactly. An example is the flaw detector [UZDL-61] (УЗДЛ-61), developed for detection of cracks on the edges of turbine blades. This instrument (Fig. 158) is designed

for control of parts whose dimensions change in insignificant limits, uses UZK of one frequency – 2.5 MHz, has one searching head radiating surface waves, is fed from a 24-volt storage battery, consuming 35 W, weighs 3 kg, screen diameter is 75 mm and dimensions are 165 × 125 × 290 mm.

An analogous instrument, the [URD-52M] (УРД-52М), developed by the TsNIIMPS for control of rails against cracks near bolt holes also works on one frequency (2.5 MHz), has a scan length calculated on height of rail (near 150 mm), and has one searching head radiating longitudinal waves. The instrument together with supply source (6-volt storage battery) is placed on a special cart rolled along the rails. For convenience of control the instrument has an indicator unit with a screen 75 mm in diameter turning around the vertical axis. For economy of power consumption of storage battery the instrument is fed by short high voltage pulses with a special vibrapack.

Specialized flaw detectors, analogous to those considered in foreign practice obviously are not used since there are no data about this in literature. Meanwhile it is possible not to recognize that development of such instruments is fully justified and in a number of cases permits a solution of specific problems of great importance, inaccessible for instruments which are more all-purpose but of greater dimensions and weight.

The most compact of portable, multipurpose flaw detectors is the [UZD-NIIM-5] (УЗД-НИИМ-5) (Fig. 159). This instrument, working on a frequency of 2.5 MHz, permits revealing defects located up to 750 mm deep in articles from materials with a small attenuation factor (forgings, rolling, welded joints). The instrument has different searching heads for work by longitudinal, shear, and surface waves; has an electron depth meter, allowing determination of coordinates of defects, an electron magnifier, allowing layered control of articles; automatic time gain control, improving detection of defects at a shallow depth; automatic signalling apparatus, giving a light or sound signal upon detection of defect; and permits manual and automatic control with recording of instrument readings in the form of an ob tive document. The UZD-NIIM-5 is designed for work in complicated workshop and field conditions and is in two units. Depending upon specific conditions of work both units can be joined as one or the feed unit can be joined to the instrument with a cable 15 m long. The instrument supply is from

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS.

Abbreviations Used in Table: Heads: [C] (С) — Combines, [S] (Р) — Separate, [S-C] (Р-С) — Separate-Combined; [R] (Пр) — Refracting. Piezoelements; [Qz] (Кв) — Quartz, [BT] (ТБ) — Barium Titanate, [LS] (ЛС) — Lithium Sulfate, [LZT] (ЦТС) — Lead Zirconate Titinate, [ASD] (АСД) — Automatic Signalling Device

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone*, mm	Dimensions of screen (diameter), mm	Amplification factor, dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
The United States													
1. Reflectoscope	Sperry	1943	0,5—1—2,25—5—12	300	—	3	12 / 2,25	230	—	200	1400×600×700	135	С. Кв. electron marks, cart
2. UR-600 Reflectoscope	Sperry	1960	0,4—1—2,25—10	300	—	9	50	150	120	—	460×360×600	34	С. Р. Пр. Кв. ТБ. ЛС (contact, immersion — broad-range), electron marks
3. Sonoray	Branson	1959	0,4÷10	—	—	—	—	100×100	—	160	280×195×520	9	С. Кв; circuits in heads, electron marks, attachment АСД
4. Reflectoscope	Republic Steel Co	1959	—	—	—	15,5	—	75	—	—	190×200×350	10	С. Кв. electron marks, spiral scan, separate feed unit
5. Echoscope 501	Corp. Curtiss-Wright	1958	0,4—1—2,25—10	—	—	—	10	—	115	—	400×300×500	25	
6. Immerscope	Curtiss-Wright	1956	—	—	—	—	—	130	—	—	—	—	For specialized immersion of stationary installation
7. Echoscope-Mark VII	Curtiss-Wright	1961	0,6—1,5—2,5—10	—		7,5	0,3 / 10	130	—	—	—	22	С and Р (contact and immersion. Кв. ТБ. ЛС. ЦТС; АСД
8. Immerscope	Douglas Aircraft Corp. (Hitt D. C.)	1955	10—25	—	—	—	—	—	—	—	—	—	Specialized immersion of stationary installation
9. UW-AB	Sperry	1960	—	—	—	—	—	—	—	—	—	—	Multipurpose instalation for research work
10. PS-800	Magnaflux	1961	0,5÷15 (6 ranges)	—	—	—	—	130	—	—	—	—	Р. Кв; separate feed unit
Poland													
11. Ultrasonic Flaw Detector Mark II	Hughes and Son	1943	0,625—1,25—2,5—2,8	—	—	—	—	130	—	—	—	—	Р. Кв. separate feed unit and scan
12. The same Mark III	The same	1943	0,625—1,25—2,5—2,8	—	—	—	—	130	—	—	—	—	Р. Кв

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone*, mm	Dimensions of screen (diameter) mm	Amplification factor, dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
13. Ultrasonic Flaw Detector Mark V	Kelvin and Hughes	1958	0,625—1,25—2,5—5	—	—	—	—	75	—	100	250×135× ×470	12,7	С, Р, Пр, Кв, ТБ, stabilizer, thickness guage attachment, АСД
14. The same Mark VI	The same	1959	0,5—1,5—2,5—5—10	—	—	2,5	—	150	—	750	315×330× ×670 3150×33× ×1670 760×610× ×1270	40 25 carriage	С, Р, Р.—С, Пр, Кв, ТБ (contact and immersion), el. marks, el. magnifier stabilizer, АСД, thickness gauge
15. Autosonics	» »	1958	1,5; 2,5; 5 and 10	—	—	—	—	300	—	—	—	—	Specialized four-channel immersion installation with recording device.
16. VIN	Ultrasonoscope		0,5—1,25—2,5—5	—	—	—	—	—	—	—	490×300× ×230	17,5	
USSR													
17. 86 IM	SNKh Lit. SSR (In-t 1 OKB)	1949	0,7—1,4—2,5—2,8	60—250	4; 2	4,5	—	125	100	200	350×225× ×500	21	Р, Кв
18. 86 IM 2		1950	0,7—1,4—2,8	150—250	5; 3	4,5	—	125	—	210	350×225× ×500	21	Р, Кв
19. 86 IM3		1953	0,7—1,5—2,5—4,0	—	—	4,5	—	125	130	210	350×225× ×500	21	С, Р, Кв, АСД
20. V4-7I		1953	0,7—1,5—2,5—4,0	—	—	5	$\frac{40}{0,7}$ $\frac{15}{1,5}$ 6/2,5/4	125	120	—	450×250× ×665	35	С, Р, Пр, Кв, ТБ, electron magnifier, electron depth meter АСД, ВРЧ
21. UZD12	LETI	1950	1,25—2,5	—	—	3	3	125	—	—	—	18	С, Кв
22. UZD14		1955	1,25—2,5	—	—	3	$\frac{5}{2,5}$	125	—	130	330×220× ×475	16	С, Пр, Кв, ТБ, electron depth meter
23. UZD16		1956	1,25—2,5	—	—	—	—	75	—	100	385×190× ×400	11	С, Пр, Кв, ТБ, electron magnifier, electron depth meter, АСД
24. UZDS18		—	0,5—1,0—1,75—2,5—4	3000	—	3	—	125	140	—	395×285× ×510	25	С, Пр, Кв, ТБ, frequency alignment

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone, mm	Dimensions of screen (diameter) mm	Amplification factor, dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
25. UZD-2	TsNIITMASh	1950	1,7	—	—	1	—	125	—	—	340×200×340	37	Р. Кв. Instrument is in the form of an attachment to cathode-ray oscilloscope
26. UZD-7N	Leningrad Council of the National Economy	1956	0,5—2,5	—	5; 1,5	—	—	75	100	75	360×220×430	16	С. П. Пр. ТБ. liquid depth meter
27. UDTs10	TsNIITMASh	1958	0,8—1,8 (or 2,5—5)	—	—	—	—	75	—	70	260×165×350	12	С. Р. Пр. ТБ. electron depth meter
28. URD52	TsNIIMPS	1952	2,5	100	5	0,25	—	75	500	15	280×320×140	3	Specialized installation on railway cart, supply self-contained С. ТБ
29. UZD55	TsNIIMPS	1955	0,8—2,5	300	—	2,5	7/2,5	75	—	40	—	—	С. Пр. ТБ
30. UZD56M	TsNIIMPS	1956	2,5	—	—	2,5	—	75	120	100	345×160×350	8	С. Пр. ТБ. [illegible] electron depth meter
31. URD58	TsNIIMPS	1958	2,5	150	10	0,2	—	75	200	12	250×380×150	3,5	Specialized installation on railway cart, self-contained supply С, ТБ
32. UZD-NIIM-2	NIIMostov	1953	2,5	110	—	1	7	75	100	120	340×320×220	6	Specialized instrument for control of welded seams, electron depth meter, electron magnifier, ВРЧ. АСД. recording С, Р. Пр. ТБ
33. UZD-NIIM-3	NIIMostov	1955	2,5	60	—	1	7	75	100	80	275×250×60	4	Specialized portable instrument. Seperate feed unit С. Р. Р—С. ТБ; el. depth meter, el. magnifier
34. UZD-NIIM-5	NIIMostov	1957	1,8; 2,5; 3,0	60	—	0,75	7	75	100	80	200×210×290	6	Specialized instrument for control of welded seams, el. depth meter, el. magnifier, АСД; С. Пр. ТБ. АСД: feed from battery or network.

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone, mm	Dimensions of screen (diameter) mm	Amplification factor dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
35. UZDL-61	207ARZ	1961	2.5	300	—	0.2	—	75	3	35	165×125×290	3÷3	Specialized instrument for control of blades of turbines heads of special types, ТБ; feed from battery
36. UDM-1M	Precision Electrical Instruments Plant	1961	0.8—1.8—2.5—5	—	—	2.5	—	75	—	110	350×200×310	13	С, Р, Р-С, Пр. Кв, ТБ; АСД: el. magnifier, el. depth meter, thickness guage attachment.
37. DUK6V	Precision Electrical Instruments Plant (Inst. and SKB UZD)	1962	0.7—1.5—2.5—4.0	2000	1—10	5.0	3	130	120	250	400×350×500	25	С. Р. Р-С. Пр. Кв. ЛС. ЦТС (contact, wear-resisting, immersion); el. magnifier, el. depth meter ВРЧ; attenuator; alignment of frequency compensation, stabilizer, АСД; cha nel for undetected amplification
38. DUK-5V	Precision Electrical Instruments Plant (SKB UZD)	1962	0.2; 0.5; 0.8; 1.5; 2.5; 5; 10	300	—	5.0	3	130	110	250	350×200×500	25	С. Р. Р-С. Пр. Кв. ЛС. ЦТС (contact, wear-res sting, immersion) el. magnifier, el. depth meter, ВРЧ; attenuator АСД; stabilizer; attachment — powerful generator, compensation ali nment of frequency
39. DUK-11IM	Precision Electrical Instruments Plant (SKB UZD and NIIMostov)	1962	2.5	100	—	0.75	7	75	100	100	280×260×180	9	Specialized instrument for control of welded joints (parameters are analogous to UZD-NIIM-5
40. DUK-8	Precision Electrical Instruments Plant (SKB UZD)	1962	0.15; 0.25; 0.5; 2.0	200—1700	—	—	—	—	—	300	330×240×500	30	Specialized instrument for control of articles from materials with large factor, Р, С (contact, immersion)
41. IDTs-3M	Precision Electrical Instruments Plant (TsNIITMASh)	1961	2.5	—	—	—	—	130	—	700	1420×950×4400	390	Specialized installation for control of pipes of diam. 6-60 mm, up to 6 mm long using normal waves by echo-method in immersion variant АСД

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone* mm	Dimensions of screen (diameter) mm	Amplification factor, dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
Austria													
42. 1000	Kretztechnik	—	1÷14	—	—	10	—	130	—	170	350×300× ×450	22	Р. С. ТБ. wear-resisting electron marks, stabilizer
43. 1000N		—	0,2÷3	—	—	10	—	130	—	170	350×300× ×450	22	For control of articles from materials with large attenuation factor.
44. 1000M		—	1÷14	—	—	75 см. воды	—	130	—	170	350×300× ×450	22	For medical articles
45. 500		—	1÷14	—	—	2	—	100	—	100	260×160× ×420	13	Simplified model
German Democratic Republic													
46. Impuls Echo-gerät	Funkwerk Erfurt	—	1; 2; 4	—	—	—	—	60× 100	—	—	350×260× ×400	—	Large set of heads, С. Р. Пр
47. «9002»	R. F. T.	—	1; 2; 4	—	—	—	50	—	—	120	370×300× ×550	25	The same
48. «9024»	R. F. T.	—	0,5—1—2—4—6	—	—	5	10/4	80× 110	—	120	270×300× ×510	25	» »
49. Sonovisor-2	Zeiss	1960	2—4	—	—	4—scan A 0,2—scan B	4	80× 550	—	50	220×340× ×440	15	Specialized instrument, allowing use of a "B" scan
Chinese Peoples Republic													
50. «Тип I»	Tsenhai' (Shanghai)	1957	1,25—2,5	—	—	10	7	80× 110	—	120	320×220× ×460	16	—
Polish Peoples Republic													
51. DI-8/S	ZEA-PW (Warsaw)	1956	0,8—1,5—3—4— 5—6	—	4,5; 1,5; 1,1	—	—	25/5	—	—	460×320× ×550	35	С. Р. Пр. Кв. ТБ. el. marks, el. magnifier
52. DI-9		—	1,5—3	—	—	—	—	—	—	—	190×160× ×250	35	Compact portable model.
53. DI-10		1959	0,4—0,8—1,5— 3—4—5—6	—	—	—	5	—	106	—	290×200× ×440	18	С. Р. Пр. Кв. ТБ. el. marks

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone* mm	Dimensions of screen (diameter) mm	Amplification factor, dB	Power drain, VA	Dimensions, mm	Weight, kg	Additional information
France													
54. Metalloradar (Type P)	Realisations Ultrasoniques	1957	1—2—3—5 (÷ one reserve 0,25÷10)	—	4; 1	5 (and 10)	5/5	—	—	165	—	30	C. P
55. Metalloradar (Type A)	Realisations Ultrasoniques	—	—	—	—	to 40	—	—	—	—	—	—	—
56. "Type A601"	Rochar	—	0,25—0,5—1—2—4—6	—	—	—	—	130×160×100	100	250	300×220×480	16	C. P
57. "Type A868"	Rochar	—	2 (or 4)	—	—	—	—	70	—	45	200×140×300	5	C. P
58. "Type A1398"	Rochar	1963	0,5—1—2—4—6—10—15	—	—	8	—	—	—	—	185×240×340	10	Compact portable transistor instrument. Feed from network 115-220 V or from storage battery 12 V АСД with spurious pulse selector
59. "Type A1245"	Rochar	1963	One working frequency (per order)	—	—	4	—	—	—	—	300×170×200	8	Compact transistor instrument. АСД in the form of an attachment.
60. "Type A1353"	Rochar	1963	One working frequency (per order)	—	—	4	—	—	—	—	280×164×100	4	Limiting compact instrument for work in difficulty accessible places. Feed from built-in battery 12 V. Instrument hangs from chest of operator.
FRG													
61. USIP-9	Krautkrämer	1957	0,25—0,5—1—2—4—6	—	—	5	—	80×100	—	—	330×240×460	18,5	Large set of heads
62. USIP-10	Krautkrämer	1960	0,5—1—2 (—2,25—4—5—6—15)	—	—	10	—	80×100	—	200	330×230×520	22	Large set of heads С. Р. Пр. Кв. ТБ. ЛС. ЦТС. el. magnifier, linear scan, АСД; attenuator, stabilizer, thickness gauge
63. USK-2	Krautkrämer	1960	2—4	—	—	1	—	75	—	—	230×150×265	4,5	Compact instrument with separate feed unit.
64. USK-4	Krautkrämer	1961	1—2—2,25—4—5—6	—	—	0,5	—	50	—	70	190×115×380	4,5	Compact transistorized ins instrument with built-in battery C. P (contact immersion)

Table 6. BASIC PARAMETERS OF PULSE ECHO-FLAW DETECTORS. (Cont'd)

Name of flaw detector	Manufacturer (developer)	Year of development	Working parts MHz	Pulse amplitude, V	Pulse duration μs	Maximum depth of sounding (steel), m	Blind zone* mm	Dimensions of screen (diameter), mm	Amplification factor, dB	Power drain VA	Dimensions, mm	Weight, kg	Additional information
65. Type II	Siemens	—	0,5—1—2,5—5	—	—	8	8	80× ×110	—	—	480×400× ×600	40	Large set of heads С. Р. Пр (contact, immersion), el. marks, el. magnifier; thickness gauge; photoadapter; undetected forces.
66. Type III	»	—	1—2,5	—	—	8	4	80× ×110	—	—	360×280× ×540	17	Large set of heads С. Р. Пр (contact, immersion), el. magnifier, linear scan АСД: photo attachment
67. Echoscope	Lehfeldt	—	0,8—2,4—4—7,2	—	—	10	3	—	120	—	340×240× ×440	24	Large set of heads С. Р. Пр (contact immersion), el. marks, linear broad-band amplifier
68. Echograph	Deutsch-Branscheid	—	0,25; 0,5; 1; 2,5; 5; 7,5; 10	—	—	10	—	—	—	—	330×250× ×480	20	С. Кв. ТБ
Czechoslovakian SSR													
69. UID-04	Chirana	1960	0,5—1—2,5—5	300	—	6	—	60× ×85	110	200	—	32	С. Р. Пр. Кв; ТБ; el. magnifier el. marks.
70. UID-S		1960	0,1—13,5	300	—	4	4/5	60× ×85	110	210	—	20	С. Р. Пр. Кв. ТБ; el. magnifier el. marks; attenuator
Japan													
71. UFD-SI	Teikoku Tsushin Kogyo Co	—	0,5—1—2—3—5—10	—	—	0,8	8	130	110	200	230×180× ×400	35	С. Р. Кв (contact, immersion el. magnifier, el. marks
72. UFD-M3		—	1—2—3—5	—	—	0,8	8	90	110	110	230×180× ×400	10	С. Кв; el. magnifier. el. marks
73. UFD-54-2C		—	1—2—3—5	500	—	—	—	—	120	—	430×350× ×660	50	С. Р. Кв (contact, immersion el. magnifier, el. marks АСД
74. UFD-5		—	1—2—3—5	—	—	0,8	—	130	100	200	290×200× ×500	22	С. Р. Кв. two-channel track; el. magnifier; el. marks; АСД: type A and B scan
75. FD-5	Mitsubishi	—	1—1,5—2—3—5	400	3÷1	3	—	120	100	200	290×200× ×500	22	С. Р. Пр. Кв. ТБ; el. marks;

*Dead band is shown in mm (numerator) at a given frequency (denominator).

a network of alternating current (220, 127, 36 or 12 V) or from a 12-volt storage battery. Power drain is ~80 W. Dimensions of instrument: 210 × 200 × 290 mm, weight 6 kg, supply unit dimensions: 210 × 200 × 130 mm, weight 5.5 kg. Diameter of indicator screen 75 mm.

In the instrument the possibility of an automatic feed of contact lubricant to searching head is forseen, which is very convenient with vertical location of surface of introduction of UZK.

Of foreign instruments belonging to the considered group an example of the most compact construction is the USK-2 (Krautkrämer, FRG). This instrument works on two frequencies – 2 and 4 MHz, is designed to detect defects up to 1 m deep (in steel), has indicator with screen diameter 75 mm, and weighs 4.5 kg. Feed unit and stabilizer weigh accordingly 5 and 7 kg and are in separate units. The feed unit can be joined as one with the basic instrument or attached to it with a long cable. In the last case the operator can use the instrument by fastening it to his chest. The instrument has a thickness gauge attachment and different searching heads, including a special head with a jet contact for control of large scale plates and sheets.

Among instruments of the considered group, a domestically manufactured instrument, the [UDM1-M] (УДМ1-М) (Fig. 160), working at frequencies 0.8; 1.8; 2.5 and 4 MHz, and designed to detect defects up to 2.5 mm deep (in steel) has wide possibilities. This instrument has searching heads for work by longitudinal waves (including a head with electrically divided radiating and receiving piezoelements possessing an insignificant dead band and sufficient sensitivity up to distances near 1 m) and also shear and surface waves. It has electron depth meters, allowing to measurment of distance to surface of reflector of located in a medium in which rate of propagation of UZK lies within the limits of 3500-6500 m/s. Analysis of parameters of a large number of instruments of the considered group shows that in these instruments as a rule:

a. Work is carried out on 2-4 previously selected frequencies within limits of a fixed range; however, in certain instruments manufactured in the United States, Austria, and the Czechoslovakian SSR, possibility of work on any frequency in these limits is provided.

b. Amplitude of electrical pulse exciting the piezoelement is 100-300 V (except the [UZDS18] (УЗДС18) of the Leningrad Electrotechnical Institute and the Japanese instrument UFD-54-2C, where this amplitude is considerably higher, and not less than 5 μs long.

c. Maximum depth of sounding (calculated for steel) is 3-5 m with individual deviations to the smaller (to 0.8 m for Japanese instruments) and larger (to 10-15 m for certain instruments in the United States) side.

d. Diameter of screen of electron-beam tube is not less than 125 mm, which improves conditions of detection of defects, but naturally causes essential increase of dimensions and weight of instruments. Weight of the majority of contemporary instruments lies within the limits of 18-25 kg, but separate instruments, including the latest developed ones, weigh up to 50 kg and more.

With such large dimensions and weight, such instruments can no longer be considered portable; frequently they are in two units with separate feed (usually with a stabilizer); special carts are used to move them.

e. A set of searching heads makes it possible to work by longitudinal, shear, surface, and normal waves with contact through a thin film of liquid, and also jet and immersion contact. The number of heads in such a set in certain instruments reaches several tens, inasmuch as along with all-purpose heads frequently there are also special heads designed for specific problems.

f. For an image free from various kinds of disturbing pulses appearing due to electrical noises in the receiving-amplifying track and also structural reverberation in the investigated metal, a special adjustment is provided ("noise cutoff"), making it possible to select a rational level of threshold sensitivity of the instrument and, at the expense of a small loss of general sensitivity, to obtain on the screen a clearer and more easily analyzed picture.

g. For comparison of amplitudes of echos in the latest instruments, variously graduated attenuators are used.

h. For fixation of control results certain instruments have photoattachments, consisting of a small camera, illuminator and discharge relay.

i. Different attachments applied to certain instruments of this group permit measuring thiskness is ≥3-4 mm, with error ≤2-3%.

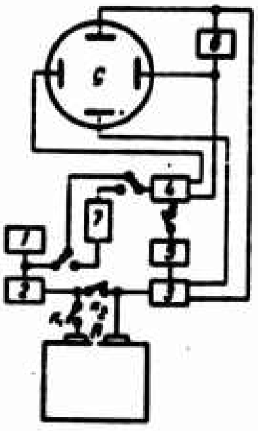


Fig. 164. Block diagram of echo-flaw detector of type V4-7I: 1 — timer; 2 — pulse generator; 3 — receiving-amplifying track; 4 — sweep generator; 5 — VR4 unit; 6 — depth meter; 7 — scan delay unit; 8 — tangent heads; 9 — electron-beam tube; K_2 and K_1 — switches for operation of combined and separate searching heads.

Examples are the Soviet echo-flaw detectors [V4-7I] (B4-7И), the USIP-10 of the Krautkrämer firm (Fig. 161). The Mark-VI from Kelvin-Hughes (Fig. 162), the UWA-B Reflectoscope from Sperry and the UFD-54 from the Japanese firm Teikoku Tsushin Kogyo Co.

The flaw detector V4-7I (Fig. 163), developed by the author with his colleagues jointly with the [OKB] (OKБ) in 1953 is widely used in our industry for control of the most crucial articles [204], and therefore will be considered in more detail. This instrument works at frequencies 0.7; 1.5; 2.5 and 4 MHz with separate searching heads on piezoelements from bariam titanate for work by longitudinal UZK on a frequency of 0.7 MHz, with combined normal searching heads on quartz piezoelements for work by longitudinal UZK on remaining frequencies, and also with refracting searching heads of different types for work by shear and surface UZK.

A block diagram of the V4-7I is shown in Fig. 164. Timer 1 is made according to the setup of a blocking generator, from the cathode of which are taken starting pulses. Repetition frequency of pulses of the timer can be smoothly regulated within the limits of 100-500 Hz. Exciter 2 is assembled on a thyratron according to the scheme of impact excitation of oscillations. Duration of pulses is regulated by a variable resistance introduced into the circuit in series.

Requirements for the receiving-amplifying track of a pulse echo-flaw detector are very high. Basic requirements: wide dynamic range of amplification, large bandwidth of transmission, and necessity of limiting decrease of cutoff time of receiving track in case of an overload.

The receiving-amplifying track of the flaw detector V4-7I satisfies the above requirements — it is built according to a circuit ensuring absence of cutoff and loss of sensitivity immediately after the action of a powerful exciter pulse on channel input.

The amplifier can work with a constant amplification factor (adjustable manually) and with a factor which automatically changes during the cycle.

It is known that sensitivity drops with increase of depth of bedding of defect.

In the control of large scale articles, for detection of deeply lying defects it is necessary to increase amplification of receiver of flaw detector. Amplification in beginning of cycle turns out to be in excess, which leads to appearance of numerous echos from structural heterogeneities of upper layers of material of article, to lengthening of initial signal and increase of dead zone. Therefore it is desirable to have variable amplification — understated in beginning of cycle and increasing by the end. For this purpose an automatic sensitivity time control is used, enabling a change of amplification factor in certain limits during the cycle and a decrease of the difference in amplitudes of echos (on screen of instrument) from defects lying at different depths. The condition of obtaining constant amplitude of voltage of echos from identical defects (on output of flaw detector) not depending on depth of bedding of defects, is expressed in the following way:

$$K(r) = Fr^2e^{2\delta r}, \tag{57}$$

where K — amplification factor; r — depth of bedding of defect; δ — attenuation factor UZK; F — proportionality factor.

From equation (57) and curves on Fig. 105 made by Yu. V. Lange [204] it follows that the law of change of amplification of receiver strongly depends on attenuation factor UZK (δ), which is especially noticeably at large distances. At small distances damping influences less than geometric divergence, however its role in these conditions is noticeable. Thus the law of change of amplification essentially depends on material of controlled article. For large distances even an inconsiderable change of attenuation factor, always existing not only in different articles but also in various sections of one article, sharply distrubs compensation. Moreover, for compensation of change of amplitude of echo in a large range of thicknesses, limits of change of amplification must be very wide. For instance, for material with attenuation factor δ = 0.04 Np/cm (structural

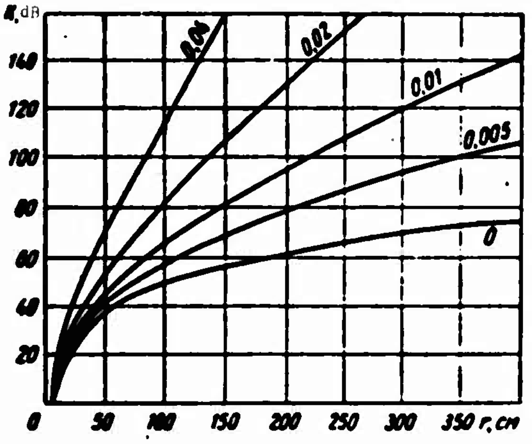


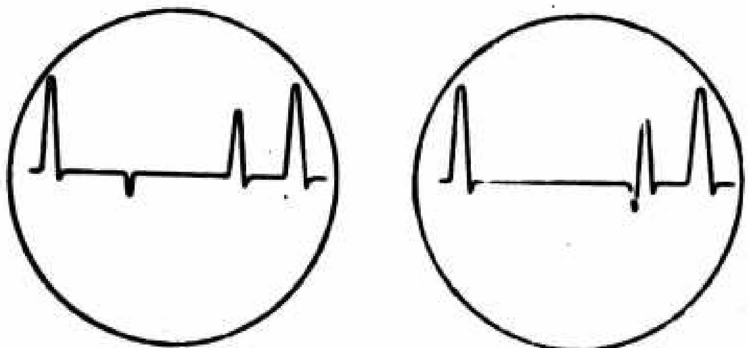
Fig. 165. Dependence of necessary change of amplification K on distance r to defect different values of attenuation factor UZK (δ). Numbers near curves — values δ, Np/cm.

steel), when controlled article is 80 cm thick, required change of amplification is 100 dB, which is fairly difficult.

In the V4-7I during automatic time adjustment amplification of first stage over about 100 μs increases from a certain initial value by ~20 dB, after which the amplification factor remains virtually constant. It is clear that such a change does not ensure compensation of signal weakening, but nonetheless gives great advantages and fully justifies itself, if only because it promotes decrease of of duration of initial signal, and consequently reduction of dead band.

The V4-7I has an electron depth meter whose basic function is measurement of distances to reflecting surfaces. It is essentially a microsecond measuring device for measurement of intervals of time from 0 to 1710 μs. Knowing time expended by a UZK pulse on passage to reflecting surface and back and also rate of propagation of pulse in a given medium, one can determine distance to reflecting surface. Besides, a depth meter permits distinguishing echo from defects from echos caused by various recesses, drillings, hollow chamfers, and flanges during control of articles of complicated form, which considerably facilitates control. Finally a depth meter permits a wide range of sufficiently (for the majority of practically important cases) accurate measurement of thickness of an article during one-sided access.

In the depth meter of the flaw detector V4-7I in order to carry out measurement, a mobile electron mark is combined with leading edge of pulse of echo from defect (Fig. 166). Such a system of reference has indubitable advantages over other known depth-measuring devices utilized in a number of foreign flaw detectors, since it eliminates the necessity of reading oscillogram time marks on the instrument screen (for instance, in the Sperry "Reflectoscope"), and permits simultaneous (with measurement) observation on screen of flaw detector of the image corresponding to the controlled article (which is impossible,



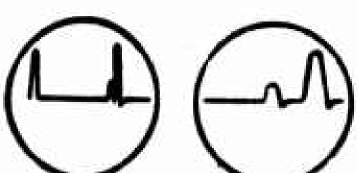
A B

Fig. 166. Measurement of depth of beading of defect by the V4-7I: A) mobile mark of depth meter is not combined with echo from defect; B) mark is combined with leading edge of echo from defect; in this position distance is read according to depth meter scale.

for instance, in the depth meter of the [UZD-7N] (УЗД-7Н)).

In the flaw detector V4-7I is special device 8 for scan delay ("electron magnifier"), improving resolving power of instrument in the control of large scale articles. In these conditions, to produce the bottom signal within limits of the screen it is necessary to decrease the image scale (increase duration of scan). Here the resolving power of the electron-beam tube begins to affect the eye of the observer, as a result of which echos close together on the screen seem coalescent. The latter leads to an impossibility of detecting a defect located sufficiently close to the bottom surface of the article.

Switching in a scan delay makes it possible to observe on the screen an image of not the whole article but only a specific zone, but then in a larger scale, where bottom echo and echo from defect are resolved sufficiently clearly (Fig. 167). It is necessary, however, to note that application of scan delay cannot infinitely increase resolving power of an instrument and to make it higher than resolving power of receiving-transmitting track of instrument.



a b

Fig. 167. Image on screen of flaw detector of two echos arriving with small difference in time: a) without electron magnifier; b) with electron magnifier.

Automation of control during work with flaw detector V4-7I is done with a special attachment – an automatic signalling apparatus of defects, the [ASD-1] (АСД-1), developed by the author

with his colleagues in 1952 [205].

The automatic signalling apparatus ASD-1 is designed for mechanized scanning of articles of simple form, and in these conditions permits controlling the fixed sounding regime with respect to level of bottom echo and noting the moment of detection of defect by appearance of echo of an assigned (or exceeding the assigned) level from a defect, activating, moreover, corresponding signals and servomechanisms. In accordance with this, the circuit of the signalling apparatus contains two independent channels: channel for bottom echo and channel for echo from defect.

The channel of the bottom echo permits controlling energy content reflected from bottom surface of article and attaining the receiving searching head. When structure of material is uniform and thickness of article is controlled zones of article is constant, if damping of UZK does not change, amplitude of bottom echo can serve as a criterion of quality of acoustic contact.

Decrease of amplitude of bottom echo can indicate also the presence of zones in the article causing raised dispersion of UZK (for instance of coarse-grained structure). By level of bottom signal from a standard sample with uniform structure it is possible to judge work of electronic circuit as a whole and quality of searching heads.

In the operation of a combined searching head amplitude of initial signal connected with direct passage of pulse of exciter through amplifier considerably exceeds amplitude of bottom signal. Therefore, since relay circuit should not operate from initial signal, channel of bottom signal uses time selection.

Time selection is applied also in channel of echo from defect, inasmuch as on input of receiving track during the working cycle there are a large quantity of different signals (sounding, multiple bottom echos, flutter echo signals from defect, echos connected with transformation of UZK upon reflection from surfaces of controlled article, pulse interferences, etc.). Time selection of pulses in combination with a noise suppression circuit permits noting appearance or change of amplitude of only those of them which by their own time position relative to beginning of working cycle can be a bottom echo or an echo from a defect and by periodicity are not pulse interferences.

The V4-7I is a representative of the third group — mobile all purpose flaw detectors.

The fourth group — stationary semiautomatic flaw detectors of high productivity — includes installations for control of intermediate products mainly of aviation industry, developed in the United States and England.

Several such installations with a different degree of automation have been developed by the Sperry firm [206] on the base of the "Reflectoscope" with an attached broad-band converter on a frequency up to 25 MHz. At first the Sperry semiautomatic machines for control of blanks of turbine disks were set up in General Motors factories under the name SIMAC (Sonic Inspection Measurement and Control), then installations were created for semiautomatic control of articles of other types. Automation is done in different ways depending upon method of acoustic contact.

When cleanness of surface treatment is of a high degree the contact can be made on flat plates, profiles, pipes, etc., through a film of contact lubricant; when cleanness of treatment is less — through a layer of flow-through liquid (jet contact). However, the basis of automation is immersion contact. Therefore immersion installations using equipment of Immerskope type, developed by Electro-Circuits (the United States); Autosonics type, developed by Kelvin and Hughes (England) and also created by Hitt for Douglas Aircraft Corp. (the United States), are immeasurably improved.

A peculiarity of these installations [207, 208] is the use of immersion contact in the use of precision kinematic devices carrying out program scanning, and also in the use of B type scan.

In the immersion variant of the echo-method the searching head and the controlled article are completely immersed in liquid (usually water), where distance between searching head and surface of article depends on thickness of article and usually is several centimeters.

Such submersion eliminates the problem of wear-resistance of searching heads and change of acoustic contact: contact is constant and very reliable, as a result of which value of bottom signal as basic indicator of reliability of acoustic contact is lost and the possibility of introduction of UZK into an article at any angle to the surface appears. Due to this requirements for cleanness of surface treatment of article disappear, since oscillations can be introduced into an article with a rough but sufficiently smooth surface (for instance

in untreated forging). With sufficient power of sounding pulse it is possible in a number of cases to use UZK of considerably higher frequencies — of the order 20-25 MHz, which in turn leads to increase of sensitivity and resolving power of method. In the immersion variant recording of flaw detector readings is considerably facilitated, and application in oscilloscopic indicator of an electron-beam tube with a long afterflow and type B scan (modulation of electron beam in brightness) permits seeing on the screen images of the contour of the controlled article and contours of sonicated part of defects of controlled section.

As was shown in Fig. 155 images on the screen during control by contact and immersion variants of the echo-method are different. In the contact variant sounding pulse and reflection from the front surface merge, in the immersion variant they are conspicuous separately. Since rate of propagation of longitudinal UZK in water is approximately four times less than in metals, the distance from searching head to front surface of controlled article should be larger than one quarter of the thickness of the article. Otherwise the second reflection from the front surface will be seen on the screen more to the left of the bottom signal, hindering deciphering of instrument readings.

During control by the echo-method in the immersion variant it is easy to carry out program scanning of an article of complicated form, inasmuch as an ultrasonic beam can be introduced into the article at any point along the normal to the surface, and in a number of cases even at a specially calculated angle which considers orientation of fiber in metal (Fig. 168). Inasmuch as the majority of metallurgical defects in deformed blanks (forgings, stampings) is oriented usually along the fiber, the problem of a program device reduces to turning the searching head so that the ultrasonic beam after refraction encounters the defect at an angle sufficiently close to 180°.

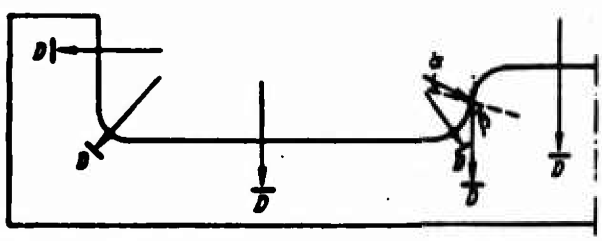


Fig. 168. Introduction of UZK into an article of complicated form, considering probable orientation of defect D.

To carry out the type B scan electron-beam tubes with a long afterglow are used. In the usual pulse echo-flaw detectors type A scan is used, in which an electron beam under the action of a sawtooth voltage fed from a sweep generator

to horizontally deflecting plates of a tube, traces on the screen a horizontal line — time axis (usually from left to right), then is extinguished while the saw is reversed, after which the process is repeated.

Pulses reflected from different obstacles (bottom echo, echo from defect) are fed to vertically-deflecting plates of tube and cause displacement of electron beam along vertical. As a result a higher image is obtained on the screen (see Fig. 155).

During type B scan the scanning sawtooth voltage is fed to one pair of plates (for instance, vertically-deflecting) and reflected pulses go to the control electrode of the electron-beam tube. The control electrode also receives constant negative voltage, extinguishing the beam throughout the direct and reverse scan. If amplitude of reflected pulses exceeds cutoff voltage, in points corresponding to moments of income of these pulses, and located on a different height a glow will be observed on the screen.

Thus, whereas during type A scan the state of homogeneity of the controlled article in a given section is represented in two coordinates on a plane; during type B scan it is depicted by one line of variable brightness. Therefore, if on the second pair of plates (horizontally-deviating) falls a voltage bias proportional to the path of advance of the searching head along the controlled article, on the screen images showing the state of homogeneity of different sections of the article will appear consecutively.

If the rate of advance of the searching head is chosen to correspond with the length of afterglow of the tube, specific points on the screen will fall into horizontal lines representing the front and back surfaces of the article, and also internal defects in them.

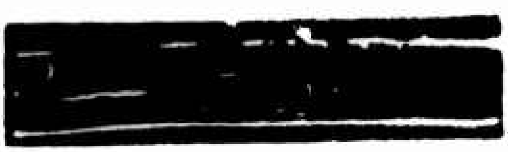


Fig. 169. Image on screen of echo-flaw detector using a tube with long afterflow and modulation of electron beam in brightness (type B scan).

Figure 169 shows the image on the screen of a tube obtained during resounding of a plate with internal defects. It is simple to estimate extent of defects and depth of their bedding. It is necessary, however, to remember that on screen is conspicuous only the reflecting surface of the defect near the surface of introduction

of oscillations, therefore for a complete representation about outlines of volume defect (for instance, a pit) it is necessary to resound in two opposite directions.

One of the most developed stationary semiautomatic immersion installations was developed by Hitt for the Douglas Aircraft Corporation. This installation is designed for control of large scale and rolled intermediate products (profiles plates) from aluminum alloy. It consists of a precision scanning mechanism, electronic equipment, and a 13.5 × 4.2 × 0.6 m bath with mobile carriage. Rate of scanning can be brought to 0.6 m/s. Scanning is done by line (given step). There is automatic reversal of carriage, and direct and reverse motion is used.

At first work is with a "survey" broad range searching head, having a piezoelement 150 mm long and mounted in a hinged holder, automatically turning so that ultrasonic beam drops on surface of article along normal following all changes of relief of this surface and holding a band around 125 mm wide. The other head is mounted in the precision manipulator (Fig. 170) allowing detailed investigation of defect by an ultrasonic beam 1.5 mm in diameter. The searching head can be fixed at different angles using a Cardan hinge rotated by servomotor.

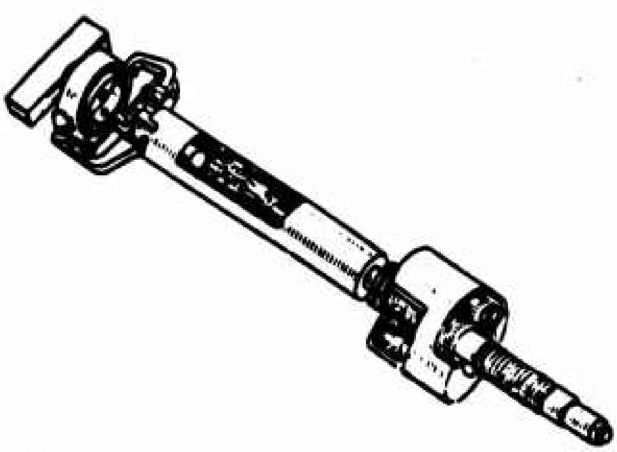


Fig. 170. Precision manipulator of the Hitt apparatus.

Work is carried out at frequencies: 2.25; 6; 10; 15 and 25 MHz, which ensures a resolving power on the highest frequency, characterized by detection of a flat reflector 1.2 mm in diameter and 2.5 mm under the surface. An automatic signalling apparatus using a light or sound signal indicates detection of a defect whose dimensions exceed the given value. An analogous installation has been made by Curtiss-Wright for the Kaiser Aluminum and Chemical Corporation.

A greatly improved immersion installation designed for control of blanks and articles of different types is the Autosonics of Kelvin and Hughes (England). This installation (Fig. 171) consists of four independent channels allowing control with automatic signalling and recording of instrument readings on paper. The installation is fed from a network through a system of stabilizers.

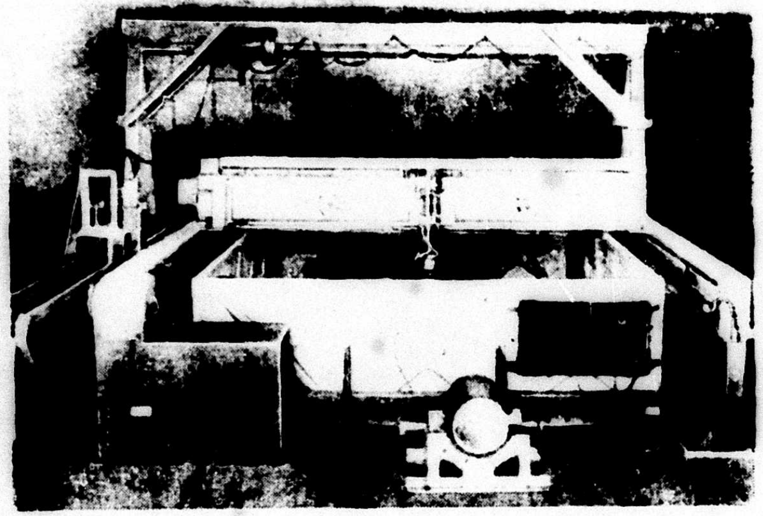


Fig. 171. Semiautomatic immersion installation, the Autosonics of Kelvin and Hughes (England).

The kinematic system constitutes a crossarm moving along guides 1.8 m apart, above a tank of fiberglass laminate plates. Width of tank is determined by distance between guides; length can be changed in wide limits since tank is made of separate sections.

Displacement rate of crossarm along guide can be regulated in wide limits — from several centimeters to several tens of meters per minute.

A special revolving table, assembled in immersion tank, permits controlling an article in the shape of a disk up to 1 m in diameter. Working frequencies: 1.5, 2.5, 5 and 10 MHz. Different searching heads can be fixed in a special manipulator, which ensures introduction of beam into article at different angles manually regulated by servomechanisms.

Before finishing our consideration of instruments typical for each of the above four groups we should consider elements of these instruments which are common for all groups. Such elements include first of all searching heads, and in smaller degree — the devices for indicating and recording the instrument readings.

The searching head is a sufficiently complicated electroacoustic converter, in many respects determining operation of flaw detector. Searching heads of the echo-flaw detector have considerably more requirements than heads the shadow flaw detector.

The theory of operation of a searching head has not yet been completed, therefore not all parameters determining its efficiency can be assigned with necessary accuracy. However, the role of certain of these parameters is already sufficiently clear and should be considered in designing searching heads and developing test methods.

In contemporary echo-flaw detectors are used searching heads designed for operation in the contact immersion and jet variants and also on excitation in controlled article of longitudinal, shear, surface, or normal waves. In design heads can be separate, combined or a combination of the two, and send UZK into the article along the normal to its surface at an acute angle to the normal, or along the actual surface.

Separate heads, in which function of UZK radiator and receiver are separated, were used in the first echo flaw detector designs. However, even at present, when the majority of problems is solved with a combined searching head, separate heads have not lost their value and in a number of cases can be used with success. The construction of separate heads is very simple.

Figure '72 gives the structural diagram of the [I-1] (И-1) head for the V4-7I, designed to introduce UZK into an article along the normal, and working on a frequency of 0.7 MHz. The head consists of aluminum body 1, protective header 2 from hardened steel silvered from both sides of piezoelement 3 from barium titanate, ebonite bushing 4, copper wire 5 soldered to silver electrode of piezoelement. and brass contact pin 6. The piezoelement is glued to the protective header with carbinol glue, the body is hermetically sealed, thus construction of head is not collapsable.

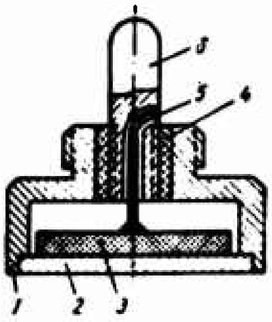


Fig. 172. Diagram of separated searching head I-1 for the echo-flaw detector V4-7I.

In the majority of domestic and foreign instruments analogous heads are in the form of a collapsable construction - piezoelement in such heads either is open or is protected from wear by a plastic cap. In the last case acoustic contact with cap is made through a film of oil, which, however, gradually dries, leading to drop of sensitivity of head.

Therefore systematic disassembly of head and lubrication of cap from within is required which is a serious exploitational deficiency of such a design.

In the operation of such "normal" heads, the dead zone (i.e., distance to the nearest defect which can be revealed), determined by directional characteristic of heads, attains considerable dimensions, as can be seen from Fig. 173. Thus for frequency $f = 2.5$ MHz an diameter of piezoelectric elements 18-20 mm, distance h_1 to point O_1, the extent of the dead zone, is around 50 mm.

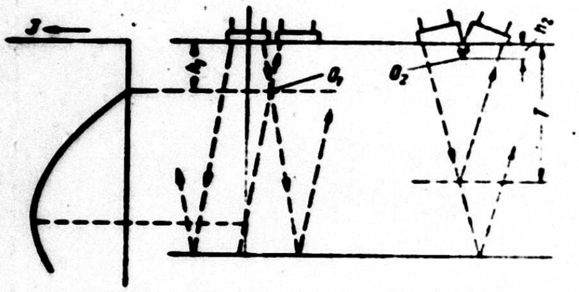


Fig. 173. Dependence of sensitivity of flaw detector on depth of bedding of defect, operating with normal heads — a, and dead zone during work with normal — b and slanted — c heads.

Sensitivity of head, conditionally shown by the curve in the left part of the figure, equal to zero within limits of dead zone starting from point O_1, gradually increases attaining maximum value at a depth corresponding to point of intersection of central beam of radiating head with lateral surface of cone (if damping is disregarded); the curve shows receiving characteristic of second receiving head after which sensitivity gradually drops with increase of depth of bedding of defect.

The dead zone can be decreased by applying slanted searching heads. In this case, as is shown on the same figure, point O_2, corresponding to location of the nearest detected defect, considerably approaches the surface of UZK introduction. However, maximum thickness of controlled article cannot be greater than T, since from bottom edge of article, lying at a larger distance, a echo cannot be obtained.

In using by heads slanted at 15°, and with piezoelements formed like a round disk the dead band is around 10-12 mm and maximum thickness of controlled article — T 150-200 mm. However, if piezoelements are shaped like a square or circle with a truncated segment, even at a 5° inclination a dead zone can be obtained (on a frequency of 2.5 MHz) around 4 mm at T = 1 m (heads of type I-3 for flaw detector V4-7I).

The design of a combined searching head is more complicated since free oscillations of the piezoelement must be damped. For this purpose the piezoelement glue to damper — a large scale body shaped like a cylinder or the frustrum of a cone, made from a material with high attenuation factor of UZK. Damper with flued piezoelement is inserted in metallic body of head; in upper part of body

is fastened a contact pin. Lower surface of piezoelement either is open (Fig. 174) or is protected by a plastic metal cap. Figure 175 gives the structural diagram of the searching I-10 to flaw detector V4-7I [209]. The head is designed to work at frequencies 1.5, 2.5 and 4.0 MHz and consists of aluminum body 3 and cover 2, quartz piezoelement 7 glued on one side to textolite damper 9 and the other to protective cap 6 (stainless steel [Ya1T] (Я1Т), 0.15 mm thick), grounding ring 8, copper wire 5 soldered to silver electrode of piezoelement, springs 10, insulating bushing and contact pin 1 (4 – slide contact). Main center of head – piezoelement with damper and protective header – cannot be disassembled, but it is easily removed from the body and replaced by another.

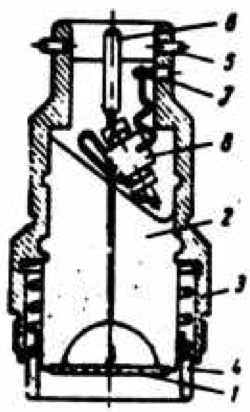


Fig. 174. Diagram of combined searching head: 1 – piezoelement; 2 – damper; 3 – body; 4 – grounding ring; 5 – pressure pin; 6 – contact pin; 7 – grounding contact; 8 – inductance coil.

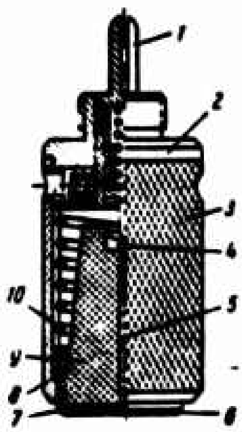


Fig. 175. Combined searching head of type I-10 to echo-flaw detector V4-7I.

The spring permits pressing converter to surface of controlled article with a constant force not depending on operator. Protective header sharply improves exploitational characteristics of head, increasing its resistance to wear. Thickness of header is not great because with increase of thickness in header flutter echoes UZK can be observed, leading to lengthening of sounding pulse and to impairment of resolving power. Advantage of metallic header as compared to plastic is small damping of UZK. Plastic caps at frequencies higher than 2.5 MHz

(due to damping of UZK) noticeably lower sensitivity of head.

To increase wear resistance of searching heads designs which involve rolling the head along the surface of the controlled article are proposed. In this case the piezoelement radiates UZK into the metal through a film of contact liquid and endless plastic tape (for instance, "vulkollan"). As the head advances the tape is rolled along the surface of the article, making the acoustic contact. Such heads are made by Krautkrämer.

Besides the considered normal heads, designed work in the contact variant of the echo-method, "immersion" heads have even greater use. Constructively they differ from "contact" heads by increased hermetic sealing of body, absence of (unnecessary in conditions of immersion contact) protective header, increased electrical strength and use as piezoelements of plates from such materials which either are not subject to the action water (or another immersion liquid) or can be protected by special coverings.

Heads designed for jet contact are used for control of articles of small thickness with flat surface (sheets, plates). Figure 176 gives the diagram of a head developed by Lehfeldt (FRG). The quartz piezoelement in this head radiates UZK into the controlled article through a column of flowing water whose height (for removal of interferences from flutter echoes of UZK in water) should be not less than one quarter of the thickness of the article.

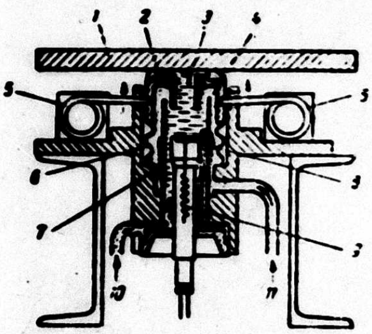


Fig. 176. Searching head with flow-through (jet) contact (Lehfeldt, FRG) for control of sheets: 1 – controlled sheet; 2 – ring; 3, 4 – water; 5 – spring; 6 – bellows; 7 – directing tube; 8 – piezoelement; 9 – inductance coil; 10 – water supply for purification; 11 – water supply for contact.

An immersion head with mobile local bath has a certain interest. In this head the piezoelement is attached inside the drum on its axis and does not change its space orientation as the drum rolls along the surface of the controlled article. Acoustic contact is made through water flooded into the drum and a rubber "tire" put on its lateral surface; it is sufficiently reliable even during a rough treatment of the surface of the article.

Refracting heads designed for excitation in controlled article of surface or shear UZK, propagating at different angles to the normal are widely used in echo-flaw detectors. Such heads in the beginning were proposed for control of welded joints, however gradually the circle of problems solved with such heads has considerably expanded.

Usually in these heads the piezoelement radiates longitudinal UZK into the body of a head made of material in which rate of propagation of UZK is considerably less than in metal. Under oblique incidence of longitudinal UZK onto the interface of two solid media with different rates of propagation of UZK refraction and transformation of UZK is observed. In the refracting head the process is somewhat complicated, inasmuch as between body of head and surface of controlled article is introduced a layer of contact liquid. Therefore refraction occurs twice: during passage through the searching head – liquid interface and then through the liquid – controlled article interface. Presence of this layer, however, acts only on quantity of energy of UZK introduced into the article – angle of refraction under which UZK propagate in an article is not changed and is determined only by the angle of incidence in the body of the head and the relationship of propagation rates of UZK in material of article and head. Excitation of shear UZK in metal as a result of refraction and transformation of longitudinal waves is possible in the immersion variant under oblique incidence of longitudinal UZK from water on the surface of metal. For this the usual immersion head must be oriented under a corresponding angle.

Body of contact refracting head ("prism") most frequently is made of plastic. The piezoelement is placed on an area oriented with the selected angle of incidence. Contact of piezoelement with body of head usually is made through a layer of oil, which is very inconvenient.

Longitudinal UZK, partially reflected from contact surface, can return to piezoelement, and due to this spurious signals can appear. To prevent this unpleasant phenomenon in the heads of different constructions various methods to remove the possibility of UZK striking the piezoelement are used. This can be done with either an absorber (Fig. 177), a special reflecting edges (Fig. 178) or by means of changing the upper part of the body of the head into a trap (sometimes of a very odd form) in which UZK repeatedly reflected from its edges

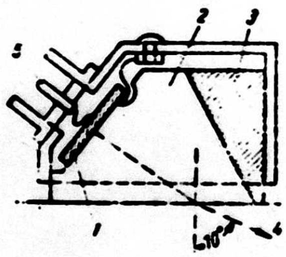


Fig. 177. Refracting searching head from Krautkrämer (FRG): 1 — piezoelement; 2 — plastic prism; 3 — absorber (damper); 4 — housing; 5 — contact pin.

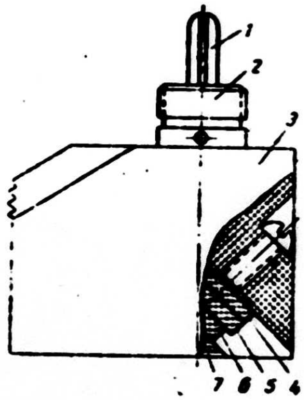


Fig. 178. Refracting searching head of type I-7 to echo-flow detector V4-7I: 1 — contact pin; 2 — bushing; 3 — plastic prism coated with zinc film; 4 — plate; 5 — damper; 6 — piezoelement; 7 — protective header.

gradually fade and do not reach the piezoelement (Fig. 179, 180) analogous to light beams in the model of an ideal black body, applied during optical measurements.

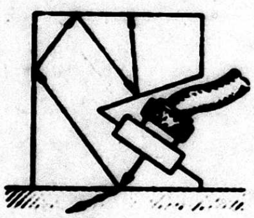


Fig. 179. Refracting searching head from TsNIITMASh with trap for reflected UZK.

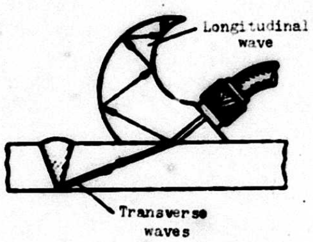


Fig. 180. Refracting searching head Ulfrasonel with trap for reflected UZK.

Under different angles, to excite shift UZK and also surface (Rayleigh) waves it is expedient to provide an adjustment of angle of incidence of beam sent by piezoconverter. For this purpose a series of designs (in domestic practice these heads are called "varialpha") in which angle of incidence can be changed by different methods: rotation of piezoelement of radiating longitudinal UZK in a liquid or in a solid medium (Fig. 181a) displacement of cap with bonded piezoelement with respect to cylindrical surface of body of head (Fig. 181 b, e), rotation relative to each other of two halves of body of head, in the form of cylinders with slanted bases (Fig. 181c), linear displacement of piezoelectric element with respect to flat surface of cap (Fig. 181d).

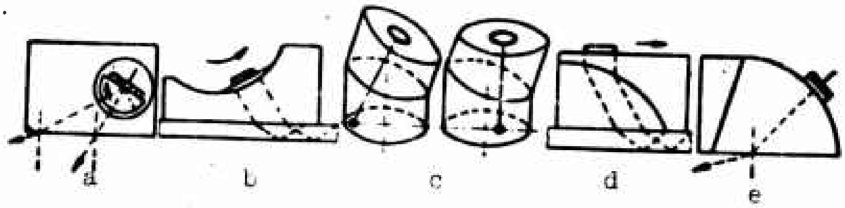


Fig. 181. Diagram of refracting searching heads with variable angle of incidence of UZK ("varialpha").

Each of these constructions, having its own advantages and disadvantages can be best used in certain conditions, but not one of them possesses an all-purpose quality. Thus, in heads made according to Fig. 181a and b when angle of incidence changes point of introduction of UZK into metal shifts into the plane of the drawing and in a head made according to Fig. 181c — also in a direction perpendicular to this plane, which is a serious deficiency essentially hampering adjustment of head.

Of all considered types of searching heads the normal head is most used. However it possesses essential deficiencies which are explained mainly by the direct electrical coupling of generator output with input to receiving-amplifying channel, which leads to an overload and cutoff of amplifier at the beginning of the cycle and consequently to an increase of the dead zone. Use of different guard circuits against overload on the amplifier input is not always the best solution: in a number of cases it is more expedient to use a separate — combined head in which radiator and receiver of UZK are constructively united in a common body which is electrically isolated. Such heads of sufficiently reliable construction are in a set of flaw detectors by Kelvin and Hughes, Krautkrämer (Fig. 182) and also the UDM1-M, and make it possible to obtain a minimum dead zone with good sensitivity.

In contemporary installations the above signalling apparatuses ASD [automatic signalling device] are used as soon as echo appears, exceeding an assigned level and taken in a defined time interval a sound or light signal immediately is switched in. Along with this indications and recording of readings of echo-flaw detector are of great value. Indication with use of an electron-beam tube can be carried out with application of different scans: an A-type scan permits obtaining image in coordinates of <u>amplitude</u> — <u>time</u>; a B scan permits observing image of section of controlled part; scan C gives an image according to plan projection

of controlled part. A combination of scans B and C, developed by Dagger [210] permits obtaining on the screen a long-term image of the revealed defect. Figure 183 schematically shows a sample (small cube) with internal stratification and the image observed on the screen of the electron-beam tube during resounding of sample in the direction shown by the pointer with different systems of scanning.

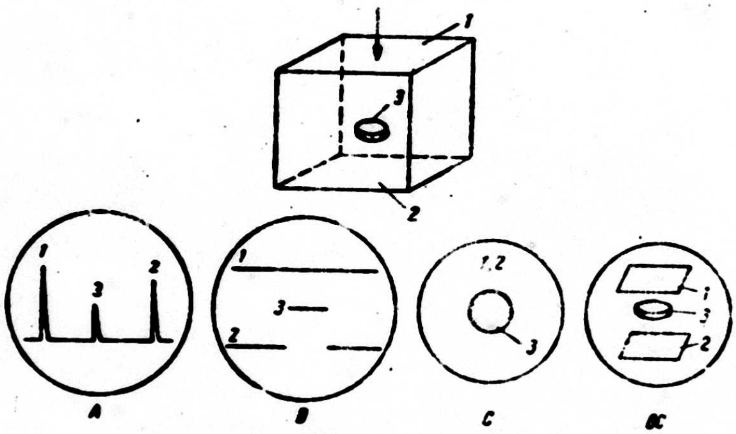


Fig. 183. Image of front (1) and rear (2) surfaces of a small cube and also internal stratification (3) in type A, B, C and BC scans.

A device for registration of the echo-flaw detector recordings — an absolutely necessary element of an automated installation, making it possible to obtain an objective document — is evidence about results of quality control of a part. If we talk about control of a large-scale part, the possibility of photographing (with a photoadapter) separate images on a screen (which permits fixing instrument readings for a narrow zone along the line of resounding) is insufficient, since registration of these readings for the whole volume of the part is necessary.

An attempt to carry out such registration by photographic means was made by Martin and Werner [211]. In front of the echo-flaw detector screen they established a camera, orienting it at 55° to the vertical (in plane to parallel to the screen). Film in the camera advanced continuously in accordance with advance of searching head along surface of part, as a result of which on the film was fixed an image similar to that shown in Fig. 184 and constituting a unique combination of scans A and B. The image gives a certain idea about homogeneity of material in a given section and extent of defects in this section, but does not

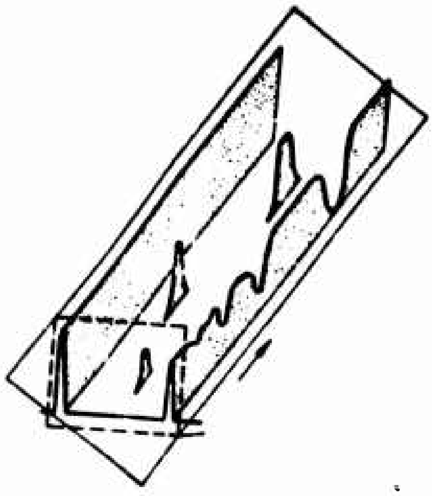


Fig. 184. Three-dimensional image of resounded part type AB scan, after Martin and Werner.

permit judging form and dimensions of defects, making it therefore very conditional. The method of Martin and Werner did not obtain practical application.

Use of self-recording devices working by a "yes — no" system or a system of proportional recording is more promising. In the first case the recording is made by a motionless "pen," making an intermittent line in accordance with arrival or cessation of signals whose amplitude exceeds an assigned level; in the second case the "pen" is fastened to a lever which deviates in a direction perpendicular to motion of paper a distance proportional to amplitude of recorded signal. Proportional recording, due to inertia of mechanism of writing systems, can be made only with a relatively low frequency — up to several hundreds of pulses per second. The recording can be made by ink lines on ordinary paper, by a heated needle on wax-coated paper, by a light beam on photographic paper, or an electrical spark on electrothermal paper. During a proportional recording every line gives a presentation about homogeneity of material only in one plane — in plane of motion of ultrasonic beam — but does not give a presentation about depth of bedding of defect. Recording results of control of a large-scale part is very difficult by a such system, since width of recording is quite considerable.

Recording by a "yes — no" system does not give a presentation either about depth of bedding of defect nor about amplitude of echo, but is more compact and therefore is more convenient for large scale parts. It is necessary to mention the "code" system of recording, sufficiently compact and giving certain information about depth of bedding of defect and about amplitude of echo [212]. All data are recorded in the form of a conditiona code (Fig. 185). Every horizontal line corresponds to one working movement of the searching head. Lines consist of groups of points where each of these groups, consisting of four points, is separated by intervals from its two neighboring groups. If there is no defect in a part, then in every group the points are disposed in one line. Upon detection of defect

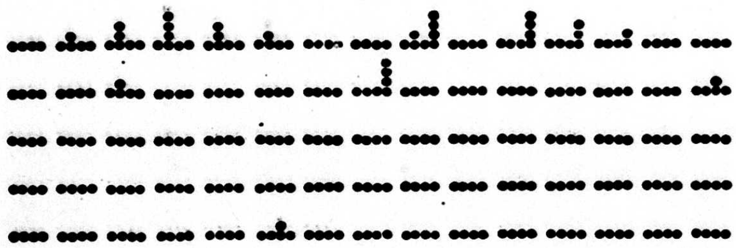


Fig. 185. Code recording of echo-flaw detector readings.

there appear additional points whose number on one vertical is proportional to amplitude of echo from the defect.

Depth of bedding of defect is determined by which of the points of a group the points indicating presence of a echo lie above. If points from defect are located above the first point of a group, the defect lies at a depth of up to 1/4 the thickness of the controlled part; if points from defect are located above the third point of a group, depth of bedding of defect lies within the limits of 1/2-3/4 the thickness of the part, etc.

Thus the diagram gives four gradations of depth of bedding of a defect, and coordinates of defect according to plan projection; consequently it is a unique combination of scans A and B and C.

Consideration of enumerated systems of recording permits affirming that not one of them satisfies all requirements of ultrasonic defectoscopy, and consequently the creation of such a system is an important problem which still waits solution.

3. General Characteristics of the Echo-Method

The echo-flaw detector is most effective only with correct selection of parameters. Basic parameters of flaw detector are adjusted in certain limits with control sticks on the instrument panel. For every specific case there is an optimum combination of different parameters.

Approaching selection of these parameters, it is necessary to know distinctly the influence of each of them on exploitational characteristics of the instrument. Incorrect selection of parameters can lead to abnormal work of instrument.

Basic indices for appraisal of exploitational characteristics of the echo-flaw detector, determining effectiveness of its work are:

a. Sensitivity, i.e., minimum area of reflector ("defect"), located in medium with defined acoustic characteristics a defined distance from point of introduction of UZK, and clearly recorded by flaw detector.

b. Range, i.e., maximum distance at which echo can be clearly registered from a reflector of given dimension located in a medium with defined acoustic characteristics.

c. Resolving power, i.e., minimum distance between two reflectors located one after the other along direction of resounding, or between reflector and "bottom" edge of article at which echos from then can be marked by indicator separately.

d. Extent of "dead band," i.e., minimum distance from point of introduction of UZK to reflector at which it can be marked by indicator.

e. Accuracy of determination of coordinates of revealed reflector ("defect").

The enumerated indices are determined by electrical and acoustic parameters of the instrument.

Physical characteristics of the controlled material also essentially influence work of the echo-flaw detector — elastic modulus, density, magnitude of grain and complexity of structure of controlled material, determining attenuation factor of UZK of different frequency in it and level of structural reverberation.

Therefore exploitational characteristics of the flaw detector must be determined for different values of attenuation factor of UZK and level of structural reverberation.

Knowledge of exploitational characteristics of a flaw detector is very important in order to judge the possibility of application of the echo-method in specific conditions and also for correct selection of electrical parameters of flaw detector and type searching heads for different practical problems.

Presence of a heterogeneity (defect) in material of the controlled article and coordinates of this defect are directly indicated by the flaw detector. However quality of article in the end is determined by dimensions and character of defect, and they must be judged by indirect indices — amplitude of echo and extent of zone in which this signal is observed (so-called conditional extent of defect).

Amplitude of echo and magnitude of conditional extent are influenced by a large number of different factors. Certain of them can be evaluated as yet only

by experimental means. In connection with this many investigations have been conducted toward calculation of these factors during control. All published research on this question have been conducted on samples (usually metallic) with artificially created heterogeneities simulating a defect. It is fully obvious, however, that imitation of a defect which is close in reflectance to the real defect is extraordinarily difficult. For instance the investigation of dependence of amplitude from such a simulated defect (on distance to it on angle of inclination to an incident ultrasonic beam) is possible virtually only reflecting surfaces are the most simple. Therefore for such investigations usually samples are used on whose end are drilled holes with a flat bottom which is the reflector of UZK. Naturally such samples cannot fully simulate real defects found in metal.

In order to obtain necessary dependences it is necessary to have a series of samples with reflectors of different diameters located various distances from point of introduction of UZK into sample and differently oriented. Preparation of such samples is difficult and does not permit sufficiently accurate simulation of natural defects. The latter can be shown using the work of Kloth [213]; investigating dependence of amplitude of echo on distance to reflector. It is clear that in connection with this it would be very important to develop a flexible and convenient method of investigating general characteristics of ultrasonic echo-method.

For this purpose the author [214] proposed, and jointly with Yu. V. Lange, carried out a method of modeling the operation of a flaw detector in water which was very effective and in a number of cases the only practically possible method of studying many interesting dependences of large value for ultrasonic defectoscopy.

Possibility of simulating the work of a flaw detector in water results from the above analogy with the operation of sonar. However, one should consider certain distinctions in conditions of propagation of ultrasonic oscillations in solid and in liquid media. First of all one should remember that whereas in a solid medium propagation of oscillations of different types — longitudinal, shear, surface normal, and others, is possible, in water only longitudinal oscillations can exist, and consequently modeling is possible only on longitudinal oscillations. Further, due to considerable difference in rate of propagation of oscillations in a solid and liquid medium, length of elastic wave in liquid (with the same

frequency) is approximately four times less than in metal. So that was kept directivity of wave field radiated by piezoconverter and reflected by "defect," determined as is known, by "wave" dimensions of piezoconverter and "defect," i.e., ratio of their parameters to length of elastic wave, it is necessary that these wave dimensions in real metal and during modeling in water be identical. Decrease of dimensions of piezoelectric converter and model of defect to carry out this condition is inexpedient. It is considerably more convenient to change (lower) frequency so that wavelength in water equals wavelength in metal.

This equivalent frequency is determined from the evident equality:

$$f_{ж} = \frac{c_{ж}}{c_{м}} \cdot f_{м},$$

where $f_{Ж}$ – frequency of UZK in water; $f_{М}$ – frequency of UZK in metal; $c_{Ж}$ – and $c_{М}$ – rates of propagation of UZK in water and metal correspondingly.

Fulfillment of this equality permits preserving (in the modelling) the same dimensions of radiator and reflector as in real conditions.

Sharp distinction of attenuation factors of UZK on equivalent frequencies in water and in metal leads to the fact that not all characteristics taken on models in water coincide with real characteristics of the pulse echo-method. This pertains to dependences connected with change of distance between radiator and reflector: these dependences determined by the method of modeling in water, will not coincide with actual dependences. In order to ensure obtaining correct characteristics, it is necessary to bring attenuation factor to the needed value, adding to water corresponding substances (for instance, glycerine), increasing this coefficient. A whole series of other characteristics not connected with change of distance, practically does not depend on attenuation factor (for instance, dependence of amplitude of echo on area or form of reflector, state of its surface, orientation, etc., at a constant distance). It is clear that in these cases the method of modeling can be applied with complete justification, where no additional correction is required.

An essential deficience of the method of modeling is that it is impossible to reproduce conditions of propagation of UZK in a heterophase, anisotropic medium (and in particular, transformation of types of oscillations during reflection and refraction, leading to considerable scattering of UZK and to appearance

of structural reverberation).

In spite of all these deficiencies, somewhat limiting application of the method of modeling, it nevertheless possesses a series of large advantages as compared to the method of investigation on metallic samples. The most important of these advantages are the possibility of rapid and smooth change of distance between radiator and reflector, and also angle between plane of reflector and incident ray, possibility of manufacture of models of reflectors of any dimensions and form: with flat surface or with a surface with any degree of roughness, possibility of excluding interference phenomena connection with reflections from lateral wall during propagation of UZK in sample with limited cross section, etc. Rational application of method of modeling permits conducting a series of interesting investigations with minimum expenditure of labor and time. A special installation was designed and prepared for research in the method of modeling (Fig. 186) consisting of a bath 740 × 440 × 330 mm, made of plastic, a kinematic device (coordinator) for displacement of heads and reflectors[1], a set of hermetically sealed heads (piezoelectric converters), panel for fastening reflectors, and a set of models of defects (reflectors).

On this installation[2] were conducted experimental investigations of basic characteristics of the echo-method; in particular dependence of amplitude of echo on distance between radiator and reflector, on area of reflector, on its form, its orientation with respect to beam, etc., were determined. These dependences are shown by curves on which experimental points are plotted with scattering which is insignificant and not Kloth.

Results of investigations, partially mentioned below, allowed an essential improvement of the widely used (USSR and abroad) method of evaluation of dimensions of revealed defects by standards in the work of normal heads, which has been reflected in instructions for ultrasonic control by the echo-method.

However a not less significant value of results of these investigations is that they confirm the possibility of deriving a fundamental equations for the pulse echo-method, analytically connecting its characteristics and enabling

[1]Coordinator designed by I. B. Kryuchkov.

[2]Investigations were made by the author together with Yu. V. Lange, B. G. Golodayev, N. V. Babkin, Z. I. Manayev, A. A. Tukkayev, A. G. Gorokhov and T. A. Borisov.

quantitative appraisal of revealed defects according to readings of the flaw detector, not resorting to comparison with standard reflectors. This is very important in arbitrary conditions, especially in the control of large scale articles when standards are very bulky and heavy.

It is clear that deriving a fundamental equation of the pulse echo-method of defectoscopy is a very complicated problem which can be solved only under a series of assumptions, which leads to essential idealization of the work of a flaw detector.

For solution of such a problem in the first approximation it is possible to use relationships known from the technology of radar and sonar, considering the above noted essential analogy in the operation of a pulse echo-flaw detector and radar especially sonar. One should, however, consider existing distinctions. Thus, diameter of radiator of pulse echo-flaw detector and length of elastic wave radiated to it are considerably less than for sonar. This leads to the necessity of making more thorough geometric definitions, inasmuch as the radiator cannot be taken as a point radiator.

Range of pulse echo-flaw detector is also comparatively small – it is measured in meters, whereas the range of sonar is in kilometers and that of radar is hundreds of kilometers. Thus, range of a flaw detector is three orders less in comparison with sonar, and five orders less in comparison with radar. This leads to the fact that a defect which is detectable by the flaw detector (even with minute dimensions) is seen from the point of radiation of UZK at an angle of sight considerably exceeding viewing angles at which a target of radar and sonar is seen.

Therefore the equation of a pulse echo-flaw detector (if it is derived just as the equation of radar and sonar, from the assumption of equal distribution of intensity of oscillations within limits of the solid angle of signt under which reflector is seen from point of radiation of UZK) will be accurate only at large distances; at small distances from point of radiation of UZK to reflector it will give noticeable error.

Thus, as follows from what has been said, during derivation of fundamental equation of pulse echo-flaw detector one should consider a series of peculiarities distinguishing the work of this instrument from the work of radar and sonars,

solving by this a great number of very complicated problems.

Obviously, depending upon accepted assumptions approximate equations can be derived by different ways. Limits of applicability of each such equation can be different, but nonetheless they must give a correct idea of relationships between basic characteristics of echo-method, and with any degree of approximation describe the quantitative side of the phenomenon.

The first equation was derived by the author in 1952 [215] on the basis of beam acoustics, assuming that radiation orginates from a point coinciding with the geometric center of the piezoelement and that intensity of UZK does not change within limits of considered solid angle. Comparison with experimental data obtained on an installation for modeling showed that this equation gives a correct dependence of amplitude of echo on distance between radiator and reflector only for very large values of these distances, and therefore for practical purposes is unfit for calculations.

In a second equation, published by the author in 1954 [216] more exact geometric construction was applied. In connection with this the idea of an imaginary focus of radiation was introduced. This equation showed good coincidence with experimental data for a wide range of distances. Figure 187 gives the dependence of amplitude of echo on distance between radiator and reflector, obtained by Yu. V. Lange by the simulation method. On the same graph are plotted data from the second equation. From comparison of curves one may see that the second equation is useful for calculations when values of distances $r > 1.8$ of extent of the Fresnel zone. At smaller distances calculated data are oversized because in deriving the equation the intensity of oscillations was assumed to be constant within the limits of the solid angle at which the reflector "is seen" from the imaginary focus of the radiator. In reality, inasmuch as for small distances this angle noticeably increases, on peripheral zones of reflector are incident UZK of smaller intensity than on the central zone, as a result of which the experimentally determined amplitudes of echos are less than those obtained by means of calculation.

Both equations are derived for the contact variant of the echo-method, and do not consider pulse operating conditions of the instrument. Naturally, in connection with development of the immersion variant, the necessity of deriving

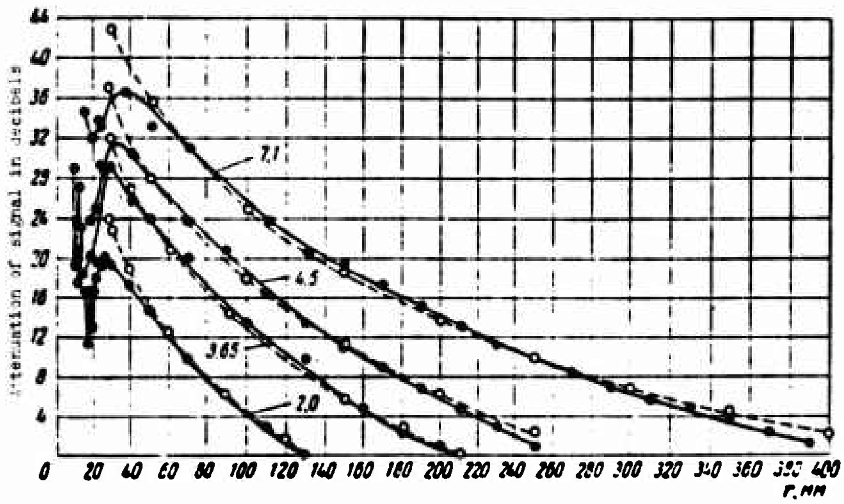


Fig. 187. Dependence of amplitude of echo on distance to reflectors of different diameter (shown in mm by figures near curves): data from calculation (o) and from experiment (●)

an all-purpose equation useful for both variants appeared.

Such a third equation was derived by author from the second. Based on presentations of beam acoustics and definitized geometric constructions used in deriving the second equation, it was possible to consider features of the contact and immersion variants[1] and also in some measure to reflect pulse operating conditions of the instrument.

The third equation is derived under the assumption that piezoconverter П (Fig. 188), in the form of a disk of diameter $D = 2a$ and area $S_{П}$, executes in turn the function of radiator and receiver of UZK, and that between piezoconverter and surface of controlled article (metal) is a layer of liquid (water) $r_{ж}$ thick.

Rate of propagation of longitudinal UZK in liquid is taken as $c_{ж}$, and in metal — c. Length of elastic wave for an assigned frequency of UZK is λ in metal and $n\lambda$ in water, where $n = c_{ж}/c$. All losses of energy of UZK propagating in a given medium are determined by a general attenuation factor, equal to $\delta_{ж}$ and δ (for liquid and metal correspondingly).

The controlled article is assumed infinitely extended in the plane to perpendicular to direction of resounding.

[1]Peculiarities of the immersion variant were first considered in the work of the author and A. G. Gorokhov, carried out in 1959 and cited below.

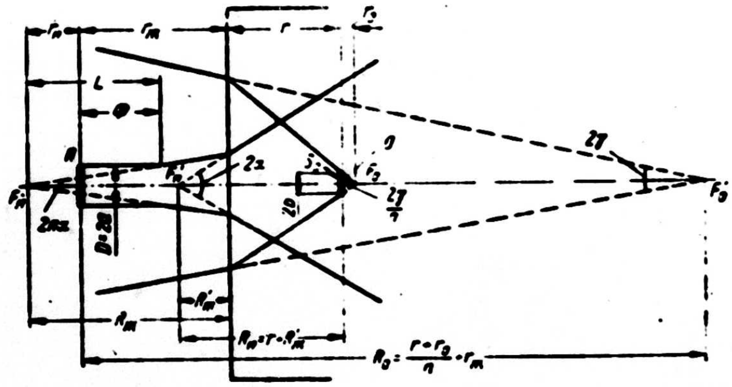


Fig. 188. Derivation scheme for echo-flaw detector equation.

It is assumed that reflector 0 ("defect"), located in controlled article at depth r under the surface, has area S_0 and is oriented perpendicularly to axis of incident beam of UZK. Inasmuch as the surface of an actual defect in general is not flat but rough, and reflection from it, even when dimensions of defect are considerable, has not a mirror but a diffuse character, the idea of an equivalent reflector is introduced, i.e., a reflector in the form of a circle 2b in diameter with a flat surface, and creating upon reflection of UZK from it the same pressure on surface of piezoconverter as a real reflector. Area of equivalent reflector is naturally less than area of a real reflector and can be expressed in the following way:

$$S_{\text{экв}} = s \cdot S_0,$$

where s — coefficient of revealability defect of given type; value of this coefficient: $s < 1$.

It is known that in direct proximity from plane of oscillating disk radiator (zone of Fresnel diffraction) almost all energy of elastic oscillations is included in a wave field having the form of a cylinder, i.e., ultrasonic beams in this field are parallel to axis of field and front of wave is flat. At a distance from plane of radiator equal to $\sim \Phi = \frac{D^2}{4\lambda}$ (where λ — length of elastic wave) begins a divergence of beams, field goes into the form of a frustum of a cone, and the wave becomes spherical. In real conditions of ultrasonic control, angles of divergence and curvature of wave front are small, which makes it possible

to ignore the effect of transformation of longitudinal waves incident on water — metal interface, and also incident on surface of defect into shear and surface waves.

In examining the divergent beam it is possible to consider that ultrasonic beam emerge from imaginary point source, $F_{И}$, lying outside plane of radiator a distance $r_{И}$ from this plane. Angle of divergence, designated in Fig. 187 by $2n\alpha$, is connected with length of elastic wave in given medium $n\lambda$ and diameter of the radiator by the relationship

$$n\alpha = \arcsin 1{,}22\frac{n\lambda}{D}.$$

Inasmuch as angles of divergence for frequencies and dimensions of radiators used in defectoscopy are small (usually 2-3° in water and 8-12° in metal, and only in individual cases 5-6° in water and 20-25° in metal), with acceptable error (≤5-6%) it is possible to replace the sine of the angle by its tangent in the cited expression.

Then: $\operatorname{tg} n\alpha = 1.22\frac{n\lambda}{D}$ and consequently:

$$r_{и} = L - \Phi = \frac{D}{2\operatorname{tg} n\alpha} - \frac{D^2}{4n\lambda} \approx 0{,}64\Phi \approx 0{,}16\frac{D^2}{n\lambda}.$$

To angle of divergence $2n\alpha$ corresponds solid angle $\Omega_{ж} =$
$= 2\pi(1 - \cos n\alpha) = 4\pi\sin^2\frac{n\alpha}{2} \approx \pi n^2\alpha^2.$

Upon passage of UZK through the water — metal interface considerable refraction will be observed, and the outside beams, entering the water at an angle $n\alpha$ to the axis of the field in the metal, will pass through at a greater angle; ratio of sines of angles of incidence and refraction are equal to n, where n is the refractive index, equal to the above ratio of rates of propagation of longitudinal UZK in liquid and in metal. For steel or aluminum in water $n \approx \frac{c_{ж}}{c} \approx 0{,}25$. Angles are small, therefore the ratio of sines of angles may be replaced by the ratio of the actual angles and to the angle of refraction may be considered as α. Thus energy of UZK introduced into metal can be considered as concentrated inside cone with vertex angle 2α, to which corresponds solid angle $\Omega = 2\pi(1 - \cos\alpha)$, or approximately (for small values α) $\Omega = \pi\alpha^2$.

It is possible to consider that ultrasonic beams are leaving imaginary point source $F'_{И}$, located in water at a distance $R'_{Ж}$ from the water — metal interface.

It is interesting to determine $R'_{ж}$ for cases when distance between converter and water — metal interface equals extent of Fresnel zone in water ($r_{ж} = \Phi$), exceeds ($r_{ж} > \Phi$) or is less than it ($r_{ж} < \Phi$), and in limit equals zero ($r_{ж} = 0$), which corresponds to conditions of work in the contact variant.

As calculation shows, the ratio of distance $R'_{ж}$ from imaginary focus $F'_{И}$ to the water — metal interface to distance $R_{ж}$ from imaginary focus $F_{И}$ to this surface for the immersion and for contact variants is equal to refractive index of UZK at transition from water into metal (in the contact variant, instead of $R'_{ж}$ we should speak of the quantity $r_{И}$).

The initial quantity for further calculation is power of UZK pulse radiated by the piezoconverter.

Let us assume that a plate of a material possessing density $\rho_{П}$, elastic modulus $E_{П}$, rate of propagation of elastic oscillations in it $c_{П}$ and piezoelectric constant for oscillations along thickness e_{11} is used as a piezoconverter. If resonance frequency of plate is f and on this frequency the plate is excited by an alternating voltage of amplitude U, in conditions of continuous oscillations in the immersion medium with specific wave impedance $\rho_{ж}c_{ж}$, a power will be radiated whose magnitudes as follows from formula (15) is

$$W = \frac{M\rho_{ж}c_{ж}e_{11}^2 f^2 \cdot \dot{Q}_{п}S_{п}U^2}{E_{п}^2}.$$

where M — proportionality factor, determined by dimension of quantities in the formula[1].

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[1]Here it is appropriate to stress once again that this formula does not consider a series of essential factors affecting magnitude of acoustic power radiated into the load. In particular, relationship of resistance of losses and resistance of radiation is not considered. During calculation on a quartz piezoconverter this does not lead to large errors, inasmuch as losses in quartz are small and acoustic eff. (η_{ak}) is close to unity. However, when using ceramics from barium titanate or lead zirconate titanate, the internal losses must be considered — in this case η_{ak} is essentially lower.

It is difficult to calculate η_{ak}, and it can be estimated as yet only very approximately. Thus Mataushek [90, p. 220] gives for a quartz converter $\eta_{ak} \approx 0.9$-0.95, and for a converter of barium titanate $\eta_{ak} \approx 0.75$-0.8. These figures, however, should be taken as critical, since they can be considerably changed depending upon design features, which a sufficiently difficult to consider.

Therefore, instead of introducing acoustic eff. η_{ak} into the initial formula (which would be in principle correct and would permit more precise determination of useful acoustic power liberated on resistance of radiation), as yet it is advisable in every specific case to determine experimentally the proportionality factor in the final formula, and subsequently, with accumulation of data, to consider η_{ak} beforehand.

In a pulse regime average power W_{cp} radiated by the piezoconverter will be

$$W_{cp} = W_{и} \cdot \tau_{и} \cdot F_{сл},$$

where $W_{и}$ – power in a pulse, $\tau_{и}$ – pulse duration, and $F_{сл}$ – pulse repetition frequency.

The resulting expression characterizes work of piezoconverter in conditions of radiation; however the power of UZK attaining the reflector surface and then, in the form of a echo reaching the surface of piezoconverter, cannot be determined by this formula because the cycle of the echo-flaw detector consists of one pulsing and the reception of the echo caused by this pulse. The subsequent pulsing can take place only after a time interval sufficient for full damping of reverberational noises. If level of reverberation is low, obviously the pause between two pulses sent one after another should in any case be larger than time expended by the pulse on passage to reflector and back. If the following pulse starts when the echo arrives, the latter will not be received separately since signals will "flood" the screen of the tube. If, however, the following pulse begins before arrival of echo, the latter will be seen on the screen in a position which does not permit a correct reading.

Thus, the highest frequency of repitition is determined by the time necessary for reception of echo from the most remote reflector during a pulse, i.e., $F_{сл} \leqslant c/2r_{max}$. The least repetition frequency is limited by decrease of brightness of image on screen of tube and permissible rate of scanning during control of large scale articles.

Increase of repetition frequency can lead also to an increased level of reverberational interferences. If the following pulse is radiated until oscillation, experiencing flutter echoes from boundaries of grains of metel and from edges of article fade, on screen of tube will appear signals corresponding to income of repeatedly reflected pulses. Inasmuch as these signals arrive after radiation of one or several following pulses, they will not be synchronized with beginning of scan and will flash on the screen, appearing randomly in different points of the scan and strongly hampering observation. Thus for calculation of processes in an echo-flaw detector, obviously one should originate from the power of a signal pulse, not from the average but from the peak determined maximum amplitude

of oscillations of piezoelement during the time of the entire pulse.

For determination of pulse power it is necessary, as was noted above, to consider the role of establishment of oscillations during work in pulse conditions. Let us consider establishment of oscillations of piezoconverter during its excitation by a high frequency square pulse.

Let us remember that when an oscillatory system in a state of rest is acted upon by an external force variable by sinusoidal law with a frequency equal to the natural frequency of oscillations of the system, amplitude of oscillations of the latter gradually increases from 0 to a certain limiting value characterizing conditions of continuous oscillations. This gradual build-up of amplitude of oscillations is the result of composition of two processes: sinusoidal oscillations with amplitude of exciting force and fading natural oscillations of the system. Amplitude A of steady-state oscillations, other things being equal, is determined by amplitude of exciting force and quality factor Q_{Π} of oscillatory system. In the process of establishment amplitude of oscillations a increases according to the law determined by the envelope equation: $a = A(1 - e^{-\alpha\tau})$, where τ — time, α — attenuation factor. The expression in parentheses we will call the pulse duration factor, and designate it $\kappa_{\text{и}}$.

Inasmuch as power of oscillations is proportional to the square of amplitude, it is possible to write

$$w = W(1 - e^{-\alpha\tau})^2,$$

or, expressing the attenuation factor by the quality factor of the system and frequency of oscillations:

$$w = W(1 - e^{-\frac{\omega\tau}{2Q}})^2.$$

Sensitivity of echo-flaw detector, determined by peak value of power in pulse, proportional to the square of maximum amplitude of oscillations, consequently increases with increase of pulse duration τ. Thus, this expression determines pulse power $W_{\text{И}}$ as a function of pulse duration:

$$W_{\text{и}} = W(1 - e^{-\frac{\omega\tau}{2Q}})^2.$$

or as a function of the number of periods in a pulse:

$$W_и = W(1 - e^{-\frac{\pi n}{2Q}})^2.$$

The given formulas are accurate, naturally, only for excitation of piezoelement by a square pulse. In general, for another pulse form pulse power (peak value) will be determined by the pulse duration factor, which should be known: $W_и = Wk_и^2$.

Upon transition through the water — metal interface, due to losses on reflection in metal UZK are introduced whose power is equal to $AW_и$, where A — energy transmission coefficient.

If we allow that intensity of UZK propagating from an imaginary source $F_и'$ in a direction normal to the piezoconverter and in directions making any angle with the normal (within limits of solid angle Ω) is identical, at the surface of the reflector this intensity will be recorded in the following way:

$$I_{пад} = \frac{AW_и \cdot e^{-2(\delta_ж r_ж + \delta r)}}{\Omega R_и^2};$$

where $R_и = r + nR_ж$.

Power of UZK attaining the reflector will be

$$W_{пад} = I_{пад} s \cdot S_0 = \frac{AW_и e^{-2(\delta_ж r_ж + \delta r)} s S_0}{\Omega R_и^2}.$$

Taking reflectivity of energy of UZK from surface of reflector as equal to β, we will obtain the power of the reflected oscillations:

$$W_{отр} = W_{пад}\beta = \frac{AW_и s S_0 \beta e^{-2(\delta_ж r_ж + \delta r)}}{\Omega R_и^2}.$$

Let us consider that the field of UZK reflected from the surface of an equivalent reflector near the reflector has the form of a cylinder, and beyond the borders of the Fresnel zone — the form of a frustum of a cone with imaginary vertex at point F_0, located beyond the plane of the reflector at distance $r_0 = 0{,}64\frac{b^2}{\lambda}$ and angle $2\frac{\gamma}{n}$ with this vertex determined from the expression $\frac{\gamma}{n} = \arcsin 0{,}61\frac{\lambda}{b}$.

Reflected UZK, upon passing the metal – water interface undergo losses on reflection a second time. When this interface is crossed refraction is observed, as a result of which the field attaining the piezoconverter will have the form of a cone with imaginary vertex at point F_0', located a distance $R_0' = \frac{r + r_0}{n}$ from the metal – water interface and with angle with 2γ, which corresponds to solid angle θ.

Intensity of reflected UZK attaining surface of piezoconverter, taking into account what has been said, will be

$$I_{пр} = \frac{AW_{отр}}{\theta R_{э}^2} e^{-2(\delta_ж r_ж + \delta r)} = \frac{A^2 W_{и} s S_0 \beta e^{-4(\delta_ж r_ж + \delta r)}}{\Omega \theta R_{и}^2 R_0^2},$$

where $R_э = \frac{r + r_0}{n} + r_ж$.

In a plane wave or when curvature of wave front is small, which corresponds to our selected conditions, intensity of oscillations is connected with amplitude of variable pressure P by the simple relationship:

$$P_{пр} = \sqrt{2\rho_ж c_ж I_{пр}}.$$

Amplitude of idling voltage developed by piezoconverter in the reception regime is equal to the product of intensity E of the electrical field in the converter by thickness of plate of piezoelement: $U_{хол} = Ed$. Intensity of field is proportional to sound pressure on surface[1] of converter: $E = g_{11} P_{пр}$, where g_{11} piezoelectric constant of pressure.

Consequently:

$$U_{хол} = g_{11} P_{пр} d.$$

This expression characterizes the work of a converter in static conditions. In oscillatory conditions and when a converter is switched into the receiving-amplifying channel input, the effective voltage, as follows from formula (22), is

$$U_{вх} = U_{хол} \frac{C_п Q_п Q_{вх}}{C_0 + C_п} = g_{11} P_{пр} d \frac{C_п Q_п Q_{вх}}{C_0 + C_п}.$$

[1]It is more correct to speak of pressure P_0 in the actual converter. Inasmuch as the converter constitutes an oscillatory system with considerable losses, in resonance conditions, in accordance with material on p. 81 we should consider $P_п > P_{пр}$. The value $\frac{P_п}{P_{пр}}$ lies from 1 to 2.

Considering the above expression for $P_{\text{пр}}$, we write:

$$U_{\text{вх}} = \frac{g_{11} d C_{\text{п}} Q_{\text{п}} Q_{\text{вх}}}{C_0 + C_{\text{п}}} \times$$

$$\times \sqrt{\frac{2MA^2 \rho_{\text{ж}} c_{\text{ж}} e_{11}^2 f^2 Q_{\text{п}} S_{\text{п}} U^2 k_{\text{и}}^2 \beta s S_0 e^{-4(\delta_{\text{ж}} r_{\text{ж}} + \delta r)}}{E_{\text{п}}^2 R_{\text{и}}^2 R_0^2 \Omega \theta}} =$$

$$= \frac{1{,}4 M^{1/2} g_{11} e_{11} d f Q_{\text{п}}^2 U k_{\text{и}} A \rho_{\text{ж}} c_{\text{ж}} e^{-2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)} Q_{\text{вх}} C_{\text{п}}}{E_{\text{п}} R_{\text{и}} R_0 (C_0 + C_{\text{п}})} \sqrt{\frac{S_{\text{п}} S_0}{\Omega \theta}} \sqrt{\beta s}\,.$$

Expressing solid angles through the corresponding plane angles, we obtain[1]

$$\sqrt{\frac{S_{\text{п}} \cdot S_0}{\Omega \theta}} \approx \sqrt{\frac{S_{\text{п}} S_0}{\pi \alpha^2 \gamma^2}} \approx \sqrt{\frac{S_{\text{п}} S_0}{14 \lambda^4}} \approx \frac{S_{\text{п}} S_0}{3{,}7 \lambda^2}\,.$$

Considering that $df = k_d$ and replacing λ by $\frac{c}{f}$, and $\frac{1{,}4\, A M^{1/2}}{3{,}7}$ by B, we write the equation of the echo-flaw detector in the following form:

$$U_{\text{вх}} = B \frac{g_{11} e_{11} k_d C_{\text{п}} S_{\text{п}} Q_{\text{п}}^2 U f^2 k_{\text{и}} \rho_{\text{ж}} c_{\text{ж}} A e^{-2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)} s^{1/2} \beta^{1/2} Q_{\text{вх}} S_0}{E_{\text{п}} (C_0 + C_{\text{п}}) c^2 R_{\text{и}} R_0}, \qquad (58)$$

where $U_{\text{вх}}$ – amplitude of echo from defect, measured on receiving-amplifying channel input;

g_{11} – piezoelectric constant of pressure of material of piezoelement;

e_{11} – piezoelectric constant of material of piezoelement;

k_d – frequency factor of material of piezoelement during oscillations of given type;

$C_{\text{п}}$ – electrical capacitance of piezoelement of searching head;

$S_{\text{п}}$ – area of radiating surface of piezoelement;

$Q_{\text{п}}$ – mechanical quality factor of searching head;

U – amplitude of voltage exciting an electrical pulse;

$k_{\text{и}}$ – coefficient of pulse duration;

f – frequency of oscillations;

$\delta_{\text{ж}}$ – attenuation factor of UZK in contact liquid;

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[1]Expressing angle θ through $\pi\gamma^2$, we allow a larger error than when replacing Ω by $\pi\alpha^2$, inasmuch as angle θ is essentially larger than angle Ω.

$r_ж$ – thickness of layer of this liquid;

δ – attenuation factor of UZK in material of controlled article;

r – depth of bedding of defect in article;

$\rho_ж c_ж$ – specific wave impedance of contact liquid;

A – transmission coefficient of energy of UZK through interface;

$Q_{вх}$ – electrical quality factor of input circuit of receiving-amplifying channel;

S_0 – area of reflector (revealed defect);

s – "revealability" of defect;

β – reflectivity of UZK from surface of defect;

$E_в$ – elastic modulus of material of piezoelement;

C_0 – input capacitance of receiving-amplifying channel;

c – rate of propagation of UZK in material of article;

$R_в$ – distance from imaginary focus of radiator to defect;

R_0 – distance from imaginary focus of defect to radiator;

B – proportionality factor.

It is clear that the resulting expression is not accurate, since during its derivation a series of assumptions was made.

However, if we compare equation (58) with equations proposed by other authors (B. N. Masharskiy [217], L. Filipchinskiy [218], I. Krautkrämer [219], it is possible to affirm that equations of these authors contain the same and even rougher assumptions and cannot ensure higher accuracy.

I. N. Yermolov [220] on the basis of considerably more strict and complicated calculation derived an equation in which general movement of the dependence of $U_{вх}'$ on S_0 coincides with equation (58), but the presence of additional terms considering nonuniform distribution of intensity of UZK within limits of the solid angle at which the reflector is seen from the point radiator essentially increases accuracy of expression.

At the same time we note that the equation of I. N. Yermolov is insufficiently clear, does not reveal roles of separate parameters, and does not permit conducting absolute calculations of the value of $U_{вх}$.

At the same time, equation (58) gives an accuracy although smaller, but fully sufficient for practical purposes, is derived very simply, graphically shows

influence of different parameters of the echo-flaw detector on its exploitational characteristics, and permits correct selection of elements of the electrical and acoustic channel, i.e., calculation of echo-flaw detector and conditions of control.

Despite the seeming complexity of the equation, it is easy to use, since almost all quantities in conditions of constant operating conditions can be preliminarily calculated, measured, or found by a table. Only four quantities: $U_{вх}$, S_0, $R_п$ and R_0, which are determined in the control process.

The equation shows how large a value has correct selection of material of converter, effectiveness of which is characterized by the quantity[1]

$$\Pi_M = \frac{g_{11} e_{11} k_d C_п}{E_п (C_0 + C_п)}. \qquad (59)$$

Obviously the best solution will be different for a converter which is combined (i.e., executing the function of radiator and receiver of UZK) and for converters which are separate, consisting of two piezoelements each of which works only as a radiator or only as a receiver.

In the second case, during calculation of Π_M the values of $E_п$, e_{11} and k_d are taken for the piezoelement working as a radiator, and the values g_{11} and $C_п$ – for one working as a receiver of UZK.

Table 7 gives the basic characteristics of piezoelectric crystals determing effectiveness of their work as converters of UZK. The table gives absolute values of the coefficient of effectiveness of converter Π_M and values of this coefficient for different combinations of piezoelectric elements (in conditions

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[1]Selection of criterion for an evaluation of the effectiveness of a piezoconverter is not a simple problem. The solution of this problem is the subject of special work (for instance [221]), in which specific recommendations are given on the basis of strict calculations. However, as a rule, in these calculations limiting conditions are assumed which are not observed in searching heads. A criterion proposed on the basis of the derived fundamental equation of the echo-flaw detector gives, of course, only qualitative relationships, which nonetheless will agree with relationships resulting from the above work. If terms considering the role of a capacitance divider on the receiver input are excluded from expression (59), it will be better to characterize properties of material of the piezoelement, and it can be used during calculation of new flaw detector. If, however, this is used expression in the given form, it is possible to select more rationally a converter for a flaw detector of defined type with known parameters.

Table 7. Basic Characteristics of Piezoelectric Crystals Determining Effectiveness of Their Work as a Converter of UZK

Material of piezoelement of combined converter or a combination of materials of radiator and receiver.	e_{hh}, N/V·m	$g_{11}\cdot 10^{-3}$, V·m/N	$K_d\cdot 10^{-3}$, m/s	$E_n\cdot 10^{-10}$, N/m^2	$\Pi'_M\cdot 10^{-10}$, m^3/N·s	$\Pi'_{M\,отн}$	$\frac{C_n}{C_0+C_n}$	$\Pi_M\cdot 10^{8}$, m^3/N·s	$\Pi_{M\,отн}$
Quartz	0,17	57	2,87	8,6	3,2	1	0,063	0,209	1
Barium titanate . . .	16,7	12	2,84	180,0	31,5	10	0,95	30	144
Lithium sulfate . .	0,9	190	2,73	6,2	75	23	0,156	11,7	56
Seignette's salt . .	0,11	160	1,2	1,0	210	65	0,25	52,5	250
Lead zirconate titanate	16,7	33	1,9	20,0	52	16	0,95	49,5	236
Lead metaniobate . .	4,8	40	1,38	0,46	58	18	0,87	50,5	242
Quartz — lithium sulfate	0,17	190	2,87	8,6	10,8	3	0,156	1,68	8
Barium titanate — lithium sulfate	16,7	190	2,84	18,0	500	156	0,156	78	370
Lead zirconate titanate — lithium sulfate . .	16,7	190	1,9	20,0	300	93	0,156	47	225
Lead metaniobate — lithium sulfate	4,8	190	1,38	0,46	270	84	0,156	42	200

of work on identical frequency), calculated with respect to coefficient of quartz, taken as one ($\Pi_{M_{отн}}$). Calculation is made for a frequency of 2.5 MHz in conditions of work with the echo-flaw detector V4-7I, for which input capacitance is 150 cm.

Analogous coefficients Π'_M and $\Pi'_{M_{отн}}$ in this table are given without taking into account the role of the capacitance divider.

Data of this table show that the most wide-spread in domestic and foreign constructions of flaw detectors, combined converters with piezoelements from quartz barium titanate are not tne best.

A considerably larger effect can be achieved by using a plate of lead zirconate titanate in a combined piezoconverter; an essential is obtained gain in sensitivity as compared to a quartz piezoelement and even as compared to a piezoelement from barium titanate. The use of Seignette's salt is very effective also, however one should remember that a piezoelement from Seignette's salt can be used only for radiation and reception of shear waves in heads of special construction.

There is even greater effect from the use of separate searching heads. From the table it may be seen that the use of identical piezoelectric materials as radiator and receiver of UZK is inexpedient. A great gain can be obtained

with the use of different materials for radiator and receiver. Thus the combination: radiator with piezoelement from barium titanate or lead zirconate titanate and receiver with piezoelement from lithium sulfate gives a gain of two orders as compared to separate converters using quartz piezoelements and almost double (without taking into account the capacitance divider – one order) as compared to converters in which both piezoelements are made of barium titanate.

We will use this conclusion in equal degree for separate searching heads of a pulse echo-flaw detector and for searching heads of the shadow flaw detector.

Experimental check confirms these considerations. For instance, the combination of lead zirconate titanate – lithium sulfate gives a gain of two orders as compared to quartz.

Obviously, when calculating and designing shadow and echo flaw detectors one should consider these considerations. However for their realization it is necessary to master the industrial production of high-quality piezoelements from lithium sulfate, lead zirconate titanate and other materials, and also to develop a design of searching heads which allows reliable protection of the lithium sulfate plate against the influence of water.

The following term of the fundamental equation, $\Pi_k = S_{п} \cdot Q_{п}$, constituting the product of area of radiator by its quality factor, also permits specific and very important conclusions relative to the rational design of a radiating piezoconverter (searching head).

Obviously, inasmuch as power of radiated UZK is proportional to area of radiator $S_{п}$, to increase sensitivity of the flaw detector this area should be increased. However, this is advisable only up to a certain optimum value above which a very important characteristic of the flaw detector worsens – accuracy of determination of coordinates of revealed defect. Accuracy of determination of coordinates of a mirror reflector of small dimensions will be maximum only if the radiator is a point radiator. Inasmuch as a point radiator does not possess directivity and radiates spherical waves, detection of a defect (i.e., taking a echo from a flat mirror reflector of small dimension) is possible only when the radiator is located at a point on the normal to surface of the reflector. When displacement of radiator in the plane parallel to the surface of the reflector is least, the echo from the reflector, as can be seen from the diagram Fig. 189a,

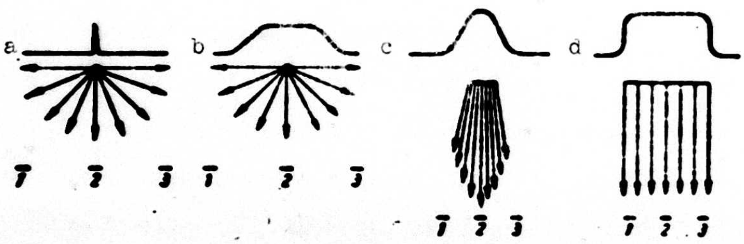

Fig. 189. Influence of dimension of radiator on accuracy of determination of coordinates of defect: a) point radiator, mirror reflector; b) point radiator, diffuse reflector; c, d) the same with increased dimensions of radiator; 1, 2, 3 — consecutive positions of defect with respect to an axis of radiator during displacement of the latter.

is not taken by the radiator.

Real defects, however are not mirror reflectors, and therefore upon displacement of radiator it will take diffuse-reflected echos. Inasmuch as diagram of directivity of a point radiator is depicted by a sphere, amplitude of taken echos will be approximately constant during displacement of radiator in sufficiently wide limits (Fig. 189b).

Thus a point radiator is unprofitable for two reasons: it does not ensure sufficient power of radiated UZK and is not accurate during determination of coordinates of defect.

With increase of diameter of radiator, its directivity at an assigned frequency increases, diagram of directivity takes a form resembling a spheriod. In this case, when radiator is located on normal to surface of reflector, amplitude of echo will be maximum, and when radiator shifts in a plane parallel to surface of reflector, although diffuse-reflected echoes will be taken, their amplitude will sharply drop with removal away from the normal (Fig. 189c); accuracy of determination of coordinates of defect increases.

As is easy to imagine, when diagram of directivity becomes narrower, level of interferences from different structural heterogeneities not located on axis of field of radiator decreases, which leads to an increase of actual sensitivity. This, with the help of sufficiently strict calculations, is shown by A. S. Golubev L. G. Merkulov and V. A. Shchukin [222].

Sharpness of fall of amplitude of echos with removal from normal will increase with decrease of width of diagram of directivity, which as is known

can be done either by increasing diameter of radiator, or by increasing of frequency of UZK. However, with increase of diameter of radiator section of central beam of UZK is increased, as a result of which echos of approximately equal amplitude can be taken by the radiator when it shifts a magnitude equal to its diameter (Fig. 189d).

From what has been said, only one conclusion can be made: for every frequency there is a radiator of optimum diameter. Decrease of this diameter leads to fall of power of radiated UZK, expansion of diagram of directivity, and consequently reduction of accuracy of determination of coordinates of revealed defect.

Increase of diameter above a certain limit leads to increase of section of beam of radiated UZK, and consequently to reduction of accuracy of determination of coordinates of defect. Besides, with increase of diameter of radiator, for a reliable acoustic contact when working in the contact variant it is necessary that the surface of the controlled article be flat and highly machined. Finally, it is necessary to note also that with increase of diameter of radiator, extent of Fresnel zone of diffraction sharply increases, power necessary for excitation of piezoconverter increases, construction is complicated, and cast of searching head is increased.

Considering all that has been presented one should recognize as rational the dimensions of piezoconverters fixed by practice (searching heads) for basic types of echo flaw detectors of domestic and foreign production. These dimensions are determined by the product of frequency (in MHz) by diameter (in cm), which for the majority of searching heads is approximately five. Thus, a piezoconverter working on a frequency of 1.5 MHz has a diameter near 3.5 cm, on a frequency of 2.5 MHz – 2 cm, on a frequency of 5 MHz – 1 cm, etc.

It is possible, however, to imagine special conditions requiring another approach to selection of diameter of piezoconverter. As is known, in the near zone of the radiator – Fresnel zone of diffraction – sensitivity of instrument sharply changes, which lowers probability of detection of defect and does not allow determination of its dimension. Inasmuch as extent of Fresnel zone is proportional to square of diameter of radiator and frequency of UZK, obviously, so that this extent is not excessively great, one should coordinate diameter of piezoconverter with frequency. It is advisable to "place" zone of Fresnel

in "dead" zone, l_{min}, at least where this is possible.

Extent of zone of Fresnel:

$$l = \frac{D^2}{4\lambda} = \frac{D^2 f}{4c} .$$

Extent of "dead" zone in accordance with [64]:

$$l_{min} = \frac{c(\tau_u + \tau_n)}{2}$$

Diameter of radiator, consequently, should be

$$D = \sqrt{\frac{4 l_0 c}{f}} = \sqrt{\frac{4c^2(\tau_n + \tau_u)}{2f}} = c\sqrt{\frac{2(\tau_n + \tau_u)}{f}} .$$

If we take duration of pulse sounding τ_u = 2 μs and duration of transition processes t_u = 3 μs, for frequencies 1.5, 2.5 and 5 MHz optimum diameter of converter will be 1.55, 1.2 and 0.85 cm correspondingly.

Searching heads made with piezoconverters of such diameters must ensure more uniform sensitivity during detection of defects located at a small depth, and in combination with usual searching heads can give a more correct idea of the dimensions of these defects.

Completely different conclusions intrude in examining the question of the quality factor Q_n of piezoconverters.

It is possible to say that all domestic and foreign searching heads, from the point of view of obtaining piezoconverters having a high quality factor, are impractical.

When area of radiator is constant power of UZK radiated into the surrounding medium is determined by amplitude of oscillations of the radiating surface. Amplitude of these oscillations for an assigned exciting force is proportional to the quality factor of the piezoconverter as an oscillatory system. Therefore, other things being equal, for more powerful UZK the quality factor of the piezoconverter should be increased. This increase cannot be infinite. Maximum quality factor of a piezoconverter is determined by the relationship of specific wave impedances of material of piezoelement and surrounding medium.

For instance, if on both sides of a radiator with specific wave impedance $\rho_n c_n$ is a medium with specific wave impedance ρc, the quality factor will be

$$Q_п = \frac{\pi}{4}\frac{\rho_п c_п}{\rho c} \approx 0{,}8\frac{\rho_п c_п}{\rho c}. \qquad (60)$$

If, however, radiation goes into media with specific wave impedance $\rho_1 c_1$ and $\rho_2 c_2$, the quality factor of a piezoconverter made of a material with specific wave impedance $\rho_п c_п$, composes as is known:

$$Q_п = \frac{\pi\rho_п c_п}{2(\rho_1 c_1+\rho_2 c_2)}. \qquad (60a)$$

For a quartz plate vibrating in air the quality factor is ~50,000, and in water – only 8. If, however, the quartz plate radiates on one side in water and on the other – air, the quality factor practically doubles and reaches 16.

These are limiting values, since they do not consider inevitable active losses introduced by constructive elements (the mounting, etc.) in the piezoconverter as in an oscillatory system. However, the biggest losses are introduced in piezoconverter as a result of artificial damping.

Searching head designs as a rule involve bonding the piezoelement to the damper – a massive body from a material with high attenuation factor of UZK (for instance, textolite) in order to maximally reduce time necessary for damping of free oscillations of piezoelement after cessation of forced oscillations.

Reduction of this time is necessary to increase resolving power of echo-flaw detector and to reduce the dead band. Magnitude of dead band l_{min} is determined by expression (55), however if we consider duration of transition processes, we should write:

$$l_{min} = \frac{c(\tau_и+\tau_п)}{2}. \qquad (61)$$

where c – rate of propagation of UZK; $\tau_и$ – duration of exciting pulse (duration of forced oscillations of piezoelement); $\tau_п$ – duration of transition process (duration of free oscillations of piezoelement).

The quality factor of a damped head can be calculated by formula (60a), placing in it the values of $\rho_1 c_1$ for material of damper and $\rho_2 c_2$ for the medium which is the load. Hueter and Bolt [88] determined the values of the quality factor in this way for a piezoconverter for different combinations of the surrounding media. However their magnitudes absolutely do not correspond to the true values

and are strongly understated because calculation by the shown formula assumes an absolutely rigid bond between piezoconverter and damper on one hand and metal (load) – on the other. In reality the piezoconverter is separated from the damper by a thin layer of glue and from the load (from controlled article), – in the contact variant of the echo-method – by a thin layer of contact lubricant. These layers possessing a certain flexibility, lower action of load on piezoconverter on the side of damper and metal. In formula (60a), therefore, one should introduce before the values $\rho_1 c_1$ and $\rho_2 c_2$ coupling coefficients K_1 and K_2, each of which is less than one:

$$Q_{п} = \frac{\pi}{2}\,\frac{\rho_{п}\,c_{п}}{K_1\rho_1 c_1 + K_2\rho_2 c_2}. \qquad (62)$$

These coefficients are simple to determine experimentally by measuring the quality factor of piezoconverter glued to damper in conditions of radiation in different loads. Thus, if we consecutively measure the Q_1 of such a converter radiating into water and Q_2 in conditions of radiation into metal through a thin layer of contact lubricant, from the first measurement is determined coefficient K_1 for the layer of glue between piezoelement and damper:

$$K_1 = \frac{\frac{\pi}{2}\,\frac{\rho_{п}c_{п}}{Q_1} - \rho_2 c_2}{\rho_1 c_1}$$

where $\rho_2 c_2$ – specific wave impedance of water or air.

Knowing K_1, from the second measurement one can determine coefficient K_2 for a layer of oil:

$$K_2 = \frac{\frac{\pi}{2}\,\frac{\rho_{п}c_{п}}{Q_2} - K_1\rho_1 c_1}{\rho_2 c_2}$$

where $\rho_2 c_2$ – specific wave impedance of material of controlled article.

Measurements carried out on several searching heads with quartz piezoelements and textolite dampers showed that the mean value of the quality factor of a head during the study in water was $Q_1 \approx 8{,}5$, and during the study in steel with a flat surface finished to $\nabla 6$ through a film of oil (pressure on searching head ~0.25 kg/cm^2), $Q_2 \approx 4$. From these data it follows that the coupling coefficient for a layer of glue $K_1 \approx 0{,}34$ and for a layer of oil $K_2 \approx 0{,}1$.

It is not difficult to show that damping action of a metallic article upon introduction of UZK through a film of contact lubricant is considerably stronger than the action of a damper separated from the piezoelement by a layer of glue. The role of such a damper increases when quality of acoustic contact is imparied (rough treatment of surface of article, accidental separation of head from this surface).

For damping to be effective, the damper should have direct acoustic contact with back surface of piezoelement. This can be done by filling the piezoelement with compound masses containing a great number of particles of highly dispersed metallic (for instance, tungsten) powder.

It is necessary, however, to stress again that effective damping for the immersion variant is unnecessary, since it leads to a sharp decrease of amplitude of oscillations, and consequently to a decrease of sensitivity.

Preservation of considerable amplitude of oscillations with simultaneous maximum decrease of pulse duration can be carried out in searching heads which have a high quality factor on the basis of methods of electrical and acoustic compensation of oscillations, developed by the author and B. G. Golodayev and considered below.

The quality factor of a piezoconverter when it operates as a searching head can affect natural frequency of plate.

It is known that in an oscillatory system with a low quality factor natural frequency of oscillations (f) is lower than in a system with a high quality factor:

$$\frac{f}{f_0} = \frac{\sqrt{4 - 1/Q^2}}{2}, \qquad (63)$$

where f_0 – natural frequency of oscillations in the absence of losses, and Q – quality factor system.

Figure 190 gives the graph of dependence of f/f_0 on Q, from which one may see that at $Q = 0.5$ natural frequency of oscillations of system becomes equal to zero, the system loses its oscillatory properties and becomes aperiodic. Then with growth of Q the quantity f/f_0 grows rapidly and even at $Q > 2$ insignificantly differs from unity. Only for $Q < 1$, for instance, $Q = 0.6$ which does not closely correspond to the real case of bilateral radiation of a quartz plate in mercury, the natural

frequency of oscillations of the piezoconverter decreasss almost by twice. Consequently, in practice for the operation of searching heads with values of quality factor higher than 4, the change of natural frequency of oscillations of converter, owing to the change of quality factor, may be disregarded.

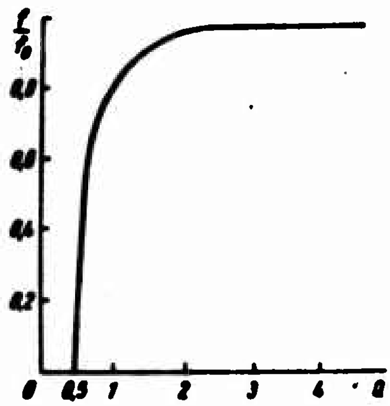

Fig. 190. Dependence of resonance frequency on quality factor of oscillatory system.

However, in a complicated oscillatory system, which a piezoconverter is, radiating in a solid semi-infinite medium through a film of contact lubricant, things are completely different. As L. Filipczinski, [223], D. B. Dianov [224] and also V. Ye. Ivanov, L. G. Merkulov and L. A. Yakovlev [225], have showed, the natural frequency of oscillations of a converter when thickness of layer of contact lubricant changes, very significantly owing to change of input impedance of load (layer of contact lubricant and controlled article).

From curves shown in Fig. 191 one may see that with increase of thickness of layer of contact lubricant (for instance, due to impairment of quality of surface treatment of controlled article) resonance frequency of quartz converter drops and amplitude of oscillations increases. Thus for wave thickness of layer equal to 0,005 (which for a frequency of UZK f = 2.5 MHz corresponds to a surface finishing of approximately Γ 6, curve 2), amplitude of oscillations at resonance increases up to 15 arbitrary units.

Points of intersection of curves with ordinate of 180°, corresponding to half-wave thickness of piezoelement, also distinctly show growth of amplitude of oscillations of piezoelement with increase of thickness of layer of lubricant. Amplitude attains maximum values when thickness of layer equals one quarter-wave. At this piezoelement radiates maximum power.

However, from this it still does not follow that work with a very thick layer is advisable, since dependences of reflectivities and passage on input impedance of the "contact lubricant — controlled article" system, i.e., on thickness of layer of lubricant are not considered here.

Figure 86 (see p. 84) gave the authors' curves of dependence of transmission coefficient [designated in numerator of equation (58)] on thickness of the layer

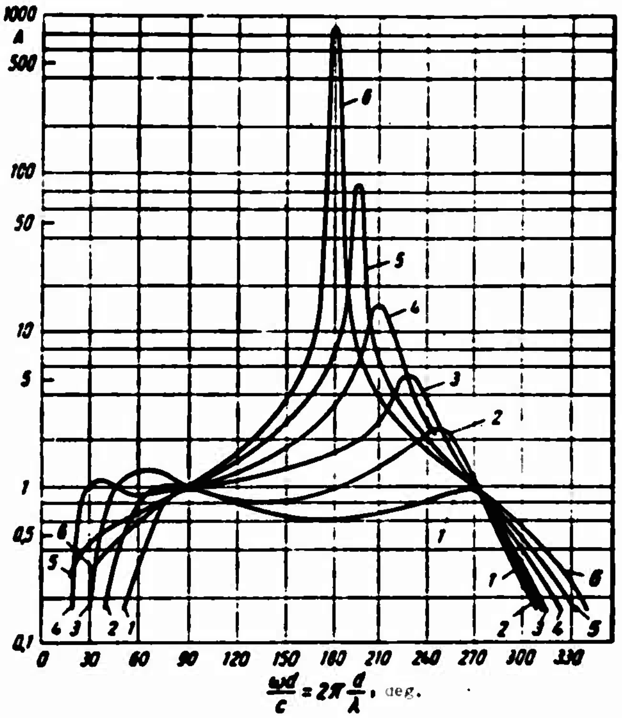

Fig. 191. Dependence of resonance frequency and resonance excess on thickness d of layer of rigidity during the study of UZK by a quartz converter in steel: A) amplitude of oscillation speed v in relative units: 1 — $d/\lambda_0 = 0$; 2 — $d/\lambda_0 = 0.03$; 3 — $d/\lambda_0 = 0.01$; 4 — $d/\lambda_0 = 0.02$; 5 — $d/\lambda_0 = 0.05$; 6 — $d/\lambda_0 =$ .25; $E = U/d =$ const

of contact lubricant (and on frequency of UZK), showing that for the above case (f = 2.5 MHz, surface treatment is the $\nabla 6 \div \nabla 4$) the transmissivity of the quartz — oil — steel system falls more then twice.

Everything said about influence of thickness of layer of lubricant on frequency and conditions of transmission of oscillations pertains to work of a converter in conditions of radiation and reception, and leads to a conclusion concerning necessity of smooth frequency tuning in echo-flaw detector. In work by the contact method in a number of cases this can give an essential gain in sensitivity.

Dependence of transmission coefficient on frequency and thickness of layer of contact lubricant in the contact echo-method makes development of method of measurement of thickness of this layer during control very desirable (for instance, by measurement of capacitance between radiating surface of searching head and surface of introduction of UZK). Knowing this thickness and consequently the transmission coefficient, it will be possible as is shown below, to determine dimensions of revealed defect during control by the contact echo-method.

The transmission coefficient in the immersion variant of the echo-method (if interface is ideally smooth) does not depend on frequency, and is determined only by relationship of specific wave impedances of immersion liquid and material of controlled article.

The following coefficient k_u in numerator of equation considers influence of pulse duration on sensitivity. If piezoconverter is excited by a high-frequency square pulse, this coefficient is $k_u = (1 - e^{-\frac{\pi n}{Q}})$. At an assigned value of the quality factor Q_n of the piezoconverter the coefficient of pulse duration

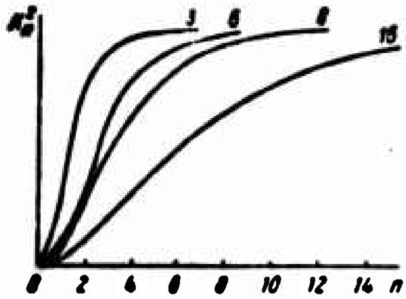

Fig. 192. Dependence of coefficient of pulse duration K_H on number of periods n in a pulse when the quality factor of the oscillatory system is different.

is conveniently expressed as a function of the number of periods:

$$k_H = \varphi(n).$$

Figure 192 gives curves of the dependence of k_H^2 on the number of periods n for different values of quality factor Q_n. The curves show that at actual values of the quality factor for pulses of small duration influence of coefficient k_H is very significant, and only for sufficiently long pulses can this influence be disregarded, inasmuch as the value of k_H^2 approaches one.

When converter is excited by a pulse of different form, magnitude of coefficient k_H should be determined in every case separately. In certain cases, for instance, under impact excitation, coefficient k_H can be taken equal to one, inasmuch as peak value of power in this case is determined by amplitude of first oscillation. Error is small in this case.

From what has been said it follows that when pulse duration increases, sensitivity slowly increases. Therefore, if a maximum solution is not required, it is possible to increase pulse duration to a certain limit above which loss in the solution will be considerably greater than gain in sensitivity. Obviously such a limit is the duration ensuring work on the section where oscillations have already formed and attained maximum amplitude.

Analyzing further numerator of equation we see that sensitivity is proportional to amplitude of voltage exciting the pulse. This amplitude should be chosen from calculation of required amplitude of voltage of echo on the receiving-amplifying channel input from a defect of given area, lying at maximum depth in an article from a material with known attenuation factor and level of structural reverberation. If dimensions of article are sufficiently great and values of attenuation factor and level of structural reverberation are high, amplitude of exciting pulse should be sufficiently great.

The following cofactor in numerator of equation is frequency of UZK, f. This quantity is to the second power in the equation, therefore the conclusion

can be made that sensitivity increases proportionally to square of frequency. However, such a conclusion will be incorrect, since influence of frequency is more complicated. First of all an increase of frequency improves conditions of reflection of UZK from obstacle, since length of elastic wave becomes small as compared to dimensions of this obstacle, fraction of reflected energy increases, and consequently sensitivity increases. Directivity of radiation is increased, which also increases sensitivity. Conditions of reception of echo reflected from surface of real defect in most cases are even more facilitated with an increase of frequency because diffuseness of reflection is increased.

However, along with this an increase of frequency leads to growth of intensity of reflection from an unevenness of surface of article and also from heterogeneities of metal which are not defects for instance, from boundaries of grains, dispersed separations, etc., which increases level of acoustic noises.

Finally, with increase of frequency attenuation factor of UZK sharply increases. Therefore dependence of sensitivity on frequency will be characterized mainly[1] by $f^2 \cdot e^{-2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)}$. Obviously this quantity for small values of the exponent $2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)$ should increase at first rapidly with increase of frequency, then slower, further, with an increase of the exponent it attains a maximum, after which it begins to decrease. Value of frequency corresponding to maximum is optimum for highest sensitivity during control of articles of assigned thickness r from a material possessing attenuation factor δ, with known frequency dependence. Figure 193 gives curves of dependence of $f^2 e^{-2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)}$ on frequency for different materials and thicknesses. In constructing these curves the quantity $\delta_{\text{ж}} r_{\text{ж}}$ was taken as zero, which led to somewhat oversized results on high (f > 15 MHz) frequencies.

These curves make possible easy orientation during selection of frequency of resounding. Thus for articles from aluminum with average grain size 0.23 mm (which corresponds to metal after rather high deformation), when thickness

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[1]When frequency changes (if diameter of radiator remains constant) certain other quantities in equation (58) will change also, for instance $R_{\text{н}}$. However, for the immersion variant of the echo-method influence of these quantities is comparatively small.

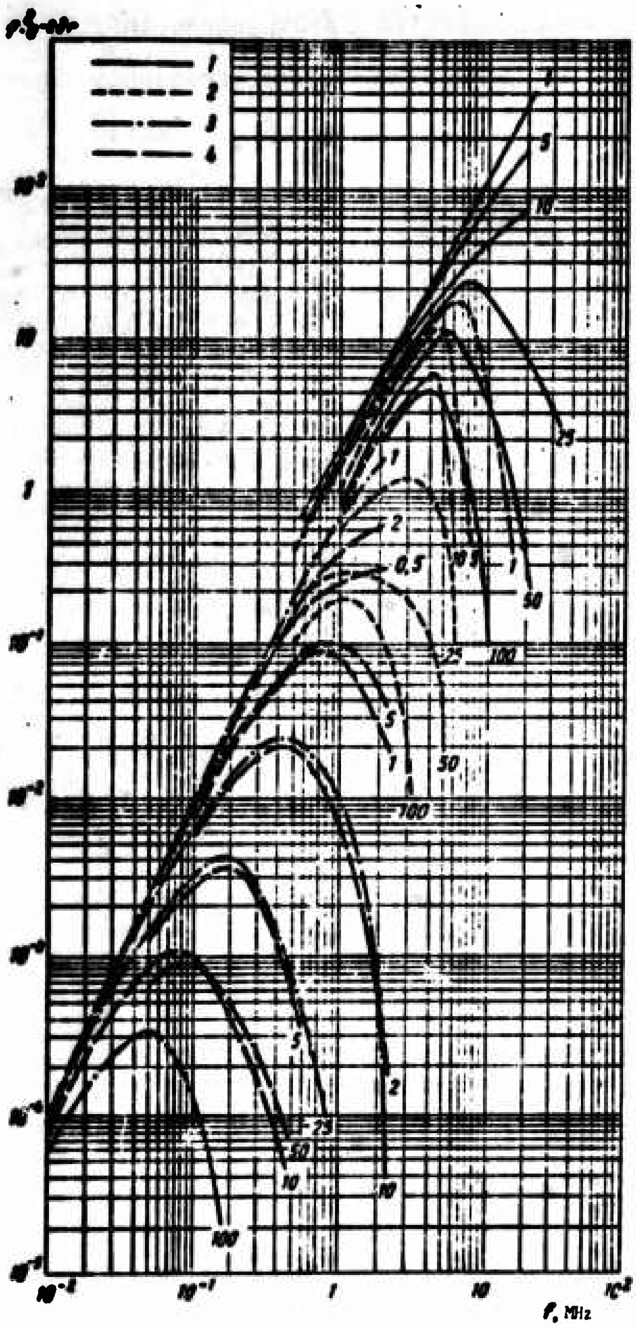

Fig. 193. Sensitivity of echo-method (criterion of sensitivity is $f \cdot e^{-2\delta r}$) depending upon frequency at different damping of UZK in material of controlled article and different thickness of article: 1 – aluminum, deformed; 2 – iron, deformed; 3 – plastic; 4 – rubber. Figures near curves – thickness of material in cm.

of article is up to 5 cm thick sensitivity (with increase of frequency up to 20 MHz) continuously increases. At a thickness of 10 cm maximum sensitivity corresponds to a frequency near 20 MHz[1], further increase of frequency does not lead to essential increase of sensitivity. For a layer of 25 cm maximum is obtained at 8 MHz; at a higher frequency sensitivity drops. Maximum for a thickness of 50 cm corresponds to 6 MHz, and for 100 cm to 4 MHz. Gradual shift of maxima to the left and constant decrease with growth of thicknesses and attenuation factors characteristic. For an article of iron with average grain size 0.12 mm, maximum on a frequency f = 6 MHz is observed even at a thickness of 1 cm. Further, for thicknesses of 5, 10, 25, 50 and 100 cm, maxima, gradually decreasing, shift to the left up to frequencies of 5, 4.5, 3, 1.5 and 1.0 MHz.

For amorphous isotropic materials with high attenuation factors (rubber, plastics) values of maxima are still lower and on the scale of frequencies they are still more to the left. Thus optimum frequency of resounding of an article of plastic 50 cm thick turns out to be 80 kHz.

The given curves are very important since they permit assigning optimum frequency range of UZK during calculation of echo-flaw detecotr, ensuring maximum sensitivity of control if attenuation factor in material of article and thickness of article of subject to control are known.

The quantity $\rho_{ж}c_{ж}$ characterizes influence of specific wave impedance of immersion liquid on sensitivity of control. The greater this quantity the higher the sensitivity of the method. Among known liquids mercury possesses a specific wave impedance whose value is an order higher than that of other liquids. However, use of mercury of an immersion liquid is impossible: mercury vapors are poisonous, it renders a harmful action on metals, and, besides, mercury is opaque (immersed in mercury, parts are invisible and adjustment of their position is hampered) is an electrical conductor (it is necessary to insulate thoroughly current-carrying parts), has great specific gravity (controlled articles float and must be fastened down).

The most acceptable immersion liquid is water. Practice, however, shows

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[1]This, of course, does not mean that control in all cases must be conducted on maximum sensitivity, since maximum sensitivity is not always optimum.

that water should be degassed (boiling, heating, prolonged exposure), especially if control is conducted on UZK of elivated frequancy. Appearance of gas bubbles in this case leads to increase of level of interferences and instability of contact.

The following cofactor in numerator of equation is transmission factor A of energy of UZK through immersion liquid - metal interface. This coefficient in the immersion variant of the echo-method is determined by ratio of specific wave impedance of liquid and metal for an ideally smooth surface, does not depend on frequency, and can be easily calculated. In the contact variant of the echo-method the transmission coefficient can be determined by Fig. 86 if magnitude of gap between contact surface of searching head and admission surface UZK into controlled article is known.

Further, in the numerator is the quantity $s^{1/2}$ - square root of revealability factor of defect. Revealability factor considers reduction of amplitude of echo from an actual in comparison with amplitude of echo from an ideal flat reflector of the same area. For defects oriented perpendicularaly to the beam, this reduction occurs as a result of diffuse reflection of UZK from the rough surface of the real defect. Consequently the ratio of amplitude of echo from defect to amplitude of echo from equivalent control flat reflector lying at a depth identical with the defect in an analogous material, or the ratio of area of control reflector to area of defect located on the same depth and giving an amplitude of echo identical with control reflector can serve as a measure of the revealability factor.

Coefficient of revealability can be determined in the following way: detecting a defect, by depth meter its depth is determined and a control reflector will selected on the corresponding standard, located on the same depth and giving a echo of the same amplitude. Then with a special drill (a "trepan") with diameter of cavity ~20 mm (or by another method) a cylinder is drilled from the controlled article, calculated so that the revealed defect completely (with a certain reserve) is contained in the section of this cylinder. Further, from the cylinder is prepared a nonstandard discontinuous sample, on its working part in the plane on which the defect is bedded a sharp cutter makes girdling line after which the sample is tensile tested. Fracture occurs along surface of defect. To measure the surface area of the defect the sample is placed

before the objective of a camera so that the axis of the sample is oriented along the optical axis of the equipment, and in the fracture plane, coaxially with the sample, is placed a flat diaphragm with a round hole whose diameter somewhat exceeds the diameter of the sample (it is possible to manage without the diaphragm if the surface of the fracture is bounded by a regular circumference). Simultaneously hole of diaphragm and fracture plane are photographed, an impression is made in sufficiently large scale (if it is necessary, by means of a "blow-up"), it is cut along the contour of the hole of the diaphragm and weighed. Then the impression is cut along the image of the defect and a second time weighed. The ratio of the obtained scales is equal to the ratio of the area of the defect and the hole of the diaphragm (ratio of these areas can be determined also by planimetry). Measuring the hole of the diaphragm, area of defect is found; by dividing area of control reflector by area of defect, the coefficient revealability is found.

Coefficient of revealability one can be determined only for defects of defined character and on a defined frequency. When frequency changes value of coefficient of revealability changes.

Inasmuch as preparation of an ideally flat control reflector in the standard of described type is sufficiently complicated and the surface of every reflector is characterized by a different degree of roughness, the coefficient of revealability is determined with respect to a specific standard and upon replacement of the standard it must be definitized.

In connection with this, necessity of development of standards of improved type, organization of centralized manufacture of these standards at someplace having the means for measurement of roughness of reflectors and certification of the set of standards becomes evident. The standards should indicate attenuation factor of UZK for different frequencies.

Determination of the coefficient of revealability for stratifications oriented in the plane parallel to the plane of introduction of UZK in forgings of aluminum alloys gave for different standards a value of the coefficient of revealability at frequencies f = 2.5 MHz and f = 1.5 MHz correspondingly of:

$$S_{2.5} = 0.25 - 0.33,$$
$$S_{1.5} = 0.32 - 0.4.$$

For analogous stratifications in stampings of heat-resistant steels of nickel and aluminum alloys, the coefficient of revealability of stratifications located in zones with different degree of deformation of metal turned out to be

$$S_{2,3} \approx 0.1 \div 0.4.$$

Knowing the revealability factor, it is possible, proceeding from the assigned area of the defect which is maximally permissible by technical conditions, to determine area of the control reflector for refection by multiplication of area of defect by this coefficient.

One factor determining magnitude of amplitude of echo is the reflectivity β of UZK from surface of defect. This coefficient is not constant, its magnitude depends basically on angle of incidence of UZK on surface of defect, on ratio of length of elastic wave to height of unevenness of surface, and on ratio of specific wave impedances of the media founded by this surface. Usually, in defectoscopy reflectivity is assumed equal to one, however, this is accurate only for cracks and pits whose surface is oriented perpendicularly to the beam. Slag, nonmetallic, oxidized, and liquational inclusions and also inclusions of alien bodies give a considerably smaller reflectivity.

In the denominator of the equation are $R_{\text{н}}$ and R_0, which for the contact echo-method can be equated with small error to the quantity r – depth of bedding of defect, but for the immersion method, they considerably exceed it. It is possible, therefore, to consider that with increase of depth of bedding of defect amplitude of echo (due to the presence of rectilinear scattering) drops for the contact echo-method somewhat faster than for the immersion method – considerably faster than follows from the law of inverse proportionality to the square of depth (under considerable damping amplitude of echo drops still faster).

It is necessary, however, to remember that we took the extent of the controlled article as infinite in the plane perpendicular to direction of resounding. If the article has such dimensions that the outermost beams do not reach lateral faces, such an assumption is valid. The less the cross section of an article, the greater the energy reflected by its lateral faces inside article. When the cross section of the article is extremely small with respect to wavelength, the article becomes its own waveguide in which rectilinear scattering is virtually

absent, weakening of sound connected with increase of area of wave front does not occur, and consequently sensitivity does not drop so sharply. Fall of sensitivity in this case is determined mainly by damping of UZK in metal.

Thus, the most profitable conditions of control are obtained during work with articles having small transverse dimensions. In this case defects can be revealed at a considerable depth.

With decrease of depth of bedding of a defect sensitivity sharply increases, however only to a certain limit determined by ratio of length of elastic wave to transverse dimensions of defect. For noticeable reflection it is necessary that dimensions of defect be comparable with wavelength. If these dimensions are less than half the wavelength UZK go around the defect, undergoing almost no reflection, and are only somewhat scattered by the defect. Intensity of scattered UZK is small, and they can be received by the piezoconverter only in the absence of interfering signals, for instance, in the control of an article from a homogeneous isotropic amorphous material (plastic). In the control of metallic articles, scattering of UZK by separate grains creates acoustic interferences against the background of which reflection from a defect whose dimensions are less than half of a wavelength is marked with difficulty.

Experimental determination of sensitivity as a function of depth of bedding of defect confirms these considerations. Curves taken for reflectors of small dimensions show that sensitivity sharply drops with increase of depth of bedding. Maximum of sensitivity corresponds to boundary of zone of plane front of wave (Fresnel zone of diffraction). In this zone UZK reflected from small obstacles and divergent at a considerable angle, attain different points of surface of piezoconverter with noticeable difference of motion, which causes an interference effect and leads to intermittent change of sensitivity.

The final purpose of control of a part is determination of dimensions of the defect revealed in it, after which the part will be recognized as suitable or considered a reject. Therefore it is especially important to establish dependence between readings of the echo-flaw detector (amplitude of echo) and dimensions of the reflector.

Considering equation (58) we arrive at a conclusion concerning linear dependence of voltage $U_{\text{вх}}$ on area of reflecting surface S_0, i.e., square dependence of this voltage on diameter of reflector. Such a conclusion, however, is not

completely accurate. It is explained by the fact that, with increase of viewing angle at which reflector is seen from an imaginary focus of the radiator, onto the reflector are incident beams of ever smaller intensity, as a result of which quantity of reflected energy increases more slowly than dimensions of the reflector. As viewing angle approaches angle of opening of diagram of directivity of radiator, growth of quantity of reflected energy is delayed even more, and after these angles become equal growth ceases. This means that the area of the reflector became equal to the area of cross section of beam of UZK, and naturally further increase of area of reflector cannot be accompanied by growth of reflected energy.

On the other hand, this should be most noticeable of all at small values of S_0, with increase of area of reflector not only is quantity of reflected energy increased, but angle of divergence of reflected UZK simultaneously decreases, which leads to faster growth of $U_{вх}$ than follows from a linear dependence. Equation (58) considers this, since the denominator (during derivation) contains angles of directivity of radiation.

Considering what has been said, it is possible to assume that for small dimensions of reflector there should be no noticeable deviation from linear dependence of $U_{вх}$ on area of reflector or, correspondingly from square dependence on diameter. Further, with increase of dimensions of reflector, this deviation becomes noticeable, and finally, when area of reflector becomes equal to cross section of beam, growth $U_{вх}$ ceases.

Figure 194 gives curve A, constructed Krautkrämer [226] according to investigation of dependence of amplitude of echo on a flat round reflector located in a "distant zone" from a "given diameter" of reflector, i.e., on the ratio of its diameter d to wavelength λ. The point of origin of this curve the author considers to be the sensitivity threshold. Sensitivity can be only insignificantly increased with the use of a highly sensitive head and an amplifier with low level of noises. In the region of given diameters (0.5-4 on figure from a to b) amplitude of echo increases approximately in proportion to the square of the given

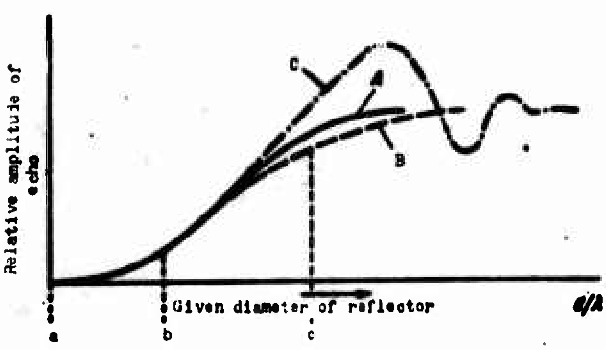

Fig. 194. Dependence of amplitude of echo on given "wave" diameter of a flat round reflector.

diameter; further, up to a value of d/λ (on figure – c) approximately equal to ratio of depth r of bedding of "defect" to diameter of radiator D, dependence is almost linear, and finally for large values of the given diameter it approaches a certain constant, inasmuch as the reflector holds the whole section of the beam of UZK.

A. G. Gorokhov constructed a curve of dependence of $U_{вх}$ on diameter of reflector on the basis of his equation of an echo-flaw detector (curve B in Fig. 194), having in general the same character as the experimental curve of Krautkrämer.

I. N. Yermolov more exactly determined the dependence of $U_{вх}$ on diameter of reflector, confirming the general movement of the curve of Krautkrämer and additionally establishing oscillatory movement of dependence of $U_{вх}$ on diameter of reflector in the "region of saturation" (curve C in Fig. 194).

Equation (58) is somewhat less accurate, however in the range of small dimensions of reflectors, i.e., in the region of the most practically interesting flaw detection of important articles this accuracy is sufficient. Besides, the advantage of equation (58) is the possibility of obtaining not only relative but also absolute data. It is possible, for instance, to calculate $U_{вх}$, if S_0 is known, and conversely, measuring $U_{вх}$, one can determine S_0.

For similar calculations it is necessary to determine the value of proportionality factor B. This can be done by calculation, substituting in the equation the values of all quantities in it in corresponding dimension.

For instance, if all quantities are expressed in the absolute system of units, and the amplitude of voltage exciting the electrical pulse is in volts, coefficient B turns out to be

$$B = 0{,}685.$$

Here $U_{вх}$ also is expressed in volts. However, inasmuch as in deriving the equation assumptions lowering accuracy were made, obviously it has meaning to determine the magnitude of coefficient B experimentally. This will allow consideration in known measure of the error caused by assumptions, and the ratio of values of coefficient B obtained experimentally and by calculation will serve as a measure of the correctness of the equation as a whole.

The author jointly with B. G. Golodayev and L. M. Zakharov measured voltage $U_{вх}$ of the echo from calibrated reflectors in the form of round drillings

with a flat bottom made in a sample of aluminum alloy.

Measurements were made a frequency of UZK of 4 MHz, diameter of quartz plate 18 mm in immersion variant of echo-method according to the diagram shown in Fig. 194 and reflectors 1-10 mm in diameter. Amplitude of exciting pulse was 146-204 V.

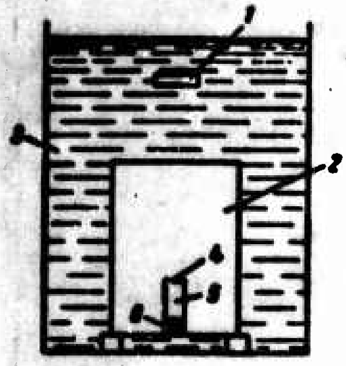

Fig. 195. Diagram of experiment in measurement of dependence of voltage $U_{\text{вх}}$ on dimensions of a flat round reflector: 1 – piezoconverter; 2 – sample (aluminum alloy); 3 – water; 4 – reflector; 5 – air; 6 – plug.

From several series of measurements the mean value of coefficient B was determined. It turned out to be 1.6 which differs from the calculated value by 2.34 times[1].

Such an insignificant divergence makes it valid to consider equation (58) sufficiently accurate for practical calculations (it is necessary only to remember that the coefficient B = 1.6 is determined for a quartz converter and for $k_{\text{д}} = 1$).

For the calculation of $U_{\text{вх}}$ equation (58) is rewritten in the following way:

$$U_{\text{вх}} = 1.6\,\frac{\varepsilon_{11} e_{11} k_{\text{д}} C_{\text{п}} S_{\text{п}} Q_{\text{п}}^{2} f^{2} k_{\text{н}} \rho_{\text{ж}} c_{\text{ж}} A s^{1/2} \beta^{1/2} e^{-2(\delta_{\text{ж}} r_{\text{ж}} + \delta r)}}{E_{\text{п}} (C_0 + C_{\text{п}}) c^{2}} \times$$

$$\times\, U Q_{\text{вх}} \frac{S_0}{R_{\text{н}} R_0}\ \text{V}. \qquad (58a)$$

After substitution of values of all quantities the calculation formula was obtained:

$$U_{\text{вх}} = 11.5 \cdot 10^{-2} U \cdot Q_{\text{вх}} \frac{S_0}{R_{\text{н}} R_0}\ \text{V}. \qquad (58b)$$

By this formula $U_{\text{вх}}$ was calculated for reflectors of different diameters. Results of calculations are shown in Fig. 196 in the form of curves showing that for small dimensions of reflector theoretical and experimental data coincide sufficiently well and that with increase of dimensions of reflector divergence gradually increases.

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[1]Taking into account the note on p. 242, the deviation between the calculated and measured value of coefficient B will be still less.

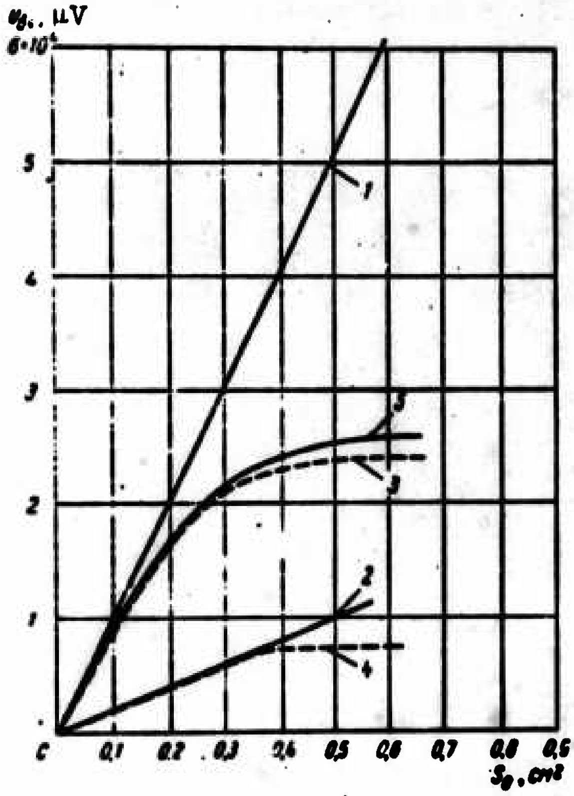

Fig. 196. Dependence of voltage $U_{вх}$ on area of a flat round round reflector: 1 – analytic curve for a long pulse (calculation by equation (58)); 2 – the same for a short pulse; 3 – experimental curve for a long pulse; 4 – the same for a short pulse; 5 – analytic curve for a long pulse calculation by equation (58) taking into account correction for irregularity of intensity of radiated UZK.

Divergence becomes noticeable during measurements made on a long pulse starting approximately from S_0 = 10-15 mm^2, and for a short pulse – S_0 = 30-35 mm^2, which corresponds to viewing angles near 1 and 2 degrees.

In the control of important articles usually it is necessary to determine dimensions of small defects whose is 5-20 mm^2. Bigger defects as a rule are not allowed, and exact determination of their dimensions is not required.

It is possible, therefore, to consider that the given curves permit determination of dimensions of revealed defects within the limits of angles of sight fully corresponding to conditions of control of important articles with sufficient accuracy for practice.

Accuracy and limits of measurement increase with decrease of pulse duration, which leads to expansion of frequency spectrum of radiated UZK, weakening of interference phenomena in field of radiator, and consequently to more uniform change of sound pressure within limits of solid angle of diagram of directivity. Therefore, from this point of view the use of limiting short pulses presents indubitable interest.

Accuracy of determination and limits of measurement of dimensions can be increased also by introducing in the calculation formula a correction considering decrease of sound pressure with increase of angle between beam and axis of radiator.

For continuous monochromatic radiation directivity of field, i.e., ratio of amplitude of sound pressure in points located identical distances from center

of radiator, in direction of field axis and in a direction making angle with this axis θ, is determined by the expression

$$G = \frac{2J_1(ka\sin\theta)}{ka\sin\theta},$$

where J_1 – Bessel function of 1st kind and order, k – wave number, a – radius of radiator. Obviously if we take directivity of fields of radiator and reflector (as identical which is a very rough approximation), the values of $U'_{\text{нх}}$ calculated by equation (58) should be multiplied by G^2.

However, it is necessary to consider that the expression for G is given for continuous radiation. In pulse conditions directivity of field decreases, and when using a maximally short pulse the radiator becomes nondirectional, i.e., pressure is equal in all directions.

Derivation of an equation determining directivity of field of radiator working in pulse conditions is complicated, and as yet is an unsolved problem, which, however, in principle obviously can be solved. Possibly, it will be sufficient to substitute the argument of the Bessel function in resulting expression.

For instance, if the argument ka sin θ were replaced by 1.5 ka sin θ, the calculated value of G^2, utilized as a correction to equation (58), permits (Fig. 197) obtaining $U_{\text{нх}}$, shown in Fig. 196 by the dotted line. As can be seen from this graph, calculated and measured values of $U_{\text{нх}}$ ideally coincide approximately up to S = 0.2 cm^2. For larger values of area of defect maximum deviation does not exceed 10%. Such coincidence should be recognized as excellent, allowing determination of dimensions of defect in a number of cases without application of standards.

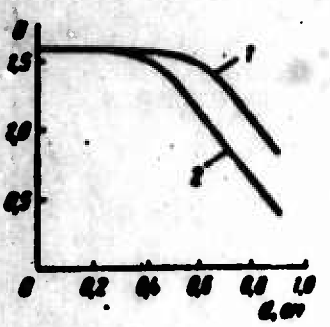

Fig. 197. Dependence of proportionality factor B in equation (58) on dimension of reflector, considering correction for irregularity of intensity of radiated UZK.

However, for such a determination to be sufficiently reliable, it is necessary to definitize obtained values of correction factor on various frequencies at a different depth of bedding of defects, at a different pulse duration, etc.

Naturally it is not necessary to reevaluate possibilities of determination of dimensions of

revealed defects by means of calculation without application of standards.

Such a determination can give good results as yet only in the control of articles from materials with low level of acoustic noises (structural reverberation). If, however, this level is sufficiently high, the receiving-amplifying channel input along with voltage of echo $U_{вх}$ is fed also voltage of acoustic noises $U_{аш}$. Detection of defect naturally is possible only if $U_{вх} > U_{аш}$. For isolation of the "useful" echo in one of the amplifier stages the previously mentioned "noise cutoff" is used, as a result of which the indicator of the echo-flaw detector shows intensive difference $U_{вх} - U_{аш}$. In this case sensitivity of echo-flaw detector is more correctly estimated by voltage developed by echo on output of instrument:

$$U_{вых} = K(U_{вх} - U_{аш}), \tag{64}$$

where K — amplification factor.

Level of structural reverberation is an inportant characteristic of alloys possessing complicated phase composition and considerable elastic anisotropy. Such alloys include many structural and heat-resistant alloys used in the manufacture of important parts in aviation and rocket construction and also in atomic reactors. The level of structural reverberation for different alloys therefore must absolutely be known in order to determine dimensions of revealed defects.

The methodology of determination of this characteristic is not developed to the degeee that it can be used in flaw detection. Attempts to calculate the level of structural reverberation permit obtaining only very tentative data.

One attempt to calculate the level of structural reverberation was made by A. S. Golubev [227] using as the first approximation a method which is analogous to that used for calculation of reverberation in the sea.

After simple transformations, the expression of A. S. Golubev takes the form

$$\frac{\sqrt{\overline{P^2_{аш}}}}{P_{пв}} = \frac{\sqrt{S_{и} c \tau_{и} \gamma_{р} e^{-4\delta r}}}{2{,}84 R_{и}}, \tag{65}$$

where $\sqrt{\overline{p_{\text{ш}}^2}}$ – mean-square value of amplitude of sound pressure of reverberational interferences on converter in the reception regime; $P_{\text{из}}$ – amplitude of sound pressure on converter in radiation regime; $S_{\text{и}}$ – area of radiating surface of converter; c – rate of propagation of UZK in investigated material; $\tau_{\text{и}}$ – pulse duration of UZK; $R_{\text{и}}$ – distance from imaginary focus of converter to source of reverberational interferences; γ_p – coefficient of scattering UZK by crystallites of the investigated material; δ – attenuation factor; r – depth of bedding of defect.

Passing from amplitude of sound pressure to intensity of UZK it is possible to transform expression (65) in the following way:

$$I_p = \frac{W_{\text{и}} c \tau_{\text{и}} \gamma_p e^{-4\delta r}}{8R_{\text{и}}^2}. \qquad (66)$$

where I_p – intensity of reverberational interference; $W_{\text{и}}$ – pulse power of converter.

Hence:

$$U_{\text{вш}} = K \frac{\varepsilon_{11} e_{11} k_{\text{д}} C_{\text{и}} S_{\text{п}}^2 Q_{\text{п}}^2 U_{i}^{2} \gamma_p^{1/2} e^{-2\delta r} A \rho_{\text{ж}} c_{\text{ж}} Q_{\text{вл}} \tau_{\text{и}}^{1/2} c^{1/2}}{E_{\text{и}} \; R_{\text{и}} (C_0 + C_{\text{и}})} \text{V}.$$

Comparing the obtained expression with equation (58), it is possible, rejecting terms playing a secondary role, to write

$$\frac{U_{\text{вх}}}{U_{\text{вш}}} = M \frac{S_{\text{и}}^{3/4} S_0}{\tau_{\text{и}}^{1/2} \gamma_p^{1/2} c^{1/2}}. \qquad (67)$$

From this expression it follows that the ratio of amplitude of "useful" echo to amplitude of interference from structural reverberation increases in proportional to the diameter of the radiator (which confirms the earlier conclusion) and area of reflector. The same ratio drops with increase of pulse duration, scattering power of medium, and rate of propagation of UZK in it. Frequency dependence level of structural reverberation, as A. S. Golubev shows, can be estimated by the quantity $\sqrt{\gamma_p} \cdot e^{-2\delta r}$. This dependence is completely analogous to the considered (Fig. 193) dependence of $U_{\text{вх}}$ on frequency.

With increase of frequency $U_{\text{вш}}$ at first grows, inasmuch as coefficient of scattering γ_p is increased. Then, with increase of index of exponential

factor growth is delayed, and $U_{\text{эш}}$ attains maximum value after which it starts to decrease.

However, inasmuch as dependence of γ_p on frequency in general is not quadratic, this maximum does not coincide with the maximum in Fig. 193. Therefore, the ratio $\frac{U_{\text{эх}}}{U_{\text{эш}}}$ will attain maximum value at a defined frequency, optimum for control of an article from a material with given level of acoustic noises. With increase of scattering power of the medium this optimum shifts to the side of lower frequencies. If for any reason either frequency of UZK is lowered in the control of articles from a material with high level of structural reverberation, it is impossible that for production of maximum ratio $\frac{Q_{\text{эх}}}{Q_{\text{эш}}}$ it is necessary to increase S_0, i.e., to lower sensitivity of echo-flaw detector, making its tuning more rough.

Finishing the consideration of possibilities of determination of sensitivity of an echo-flaw detector and dimensions of revealed defects by means of calculation without application of standards, one should note that all methods proposed by different authors, including the method of calculation by equation (58), anticipate use of tabular values of attenuation factor, which in many cases can serve as a source of considerable errors. Avoidance of these errors is possible by using a special method of calculation developed by the author and A. A. Tukkayev and described in the following section.

4. Method of Control and Ways for Improvement

a. General Considerations

Reliability of control is determined by correctness of selection and thoroughness of development of method of control, for which it is necessary to know characteristics of the controlled article, material from which it is made, and also defects which must be revealed[1].

Basic characteristics of the controlled article determining method of control are: a) technology of manufacture; b) form and dimensions; c) state of surface; d) allowances on treatment; e) condition of load in exploitation; f) volume of production.

[1]This section considers methodology of control by the echo-method. Many positions can also be used in control by other ultrasonic methods.

Characteristics of material: a) chemical and phase composition; b) degree of deformation; c) macrostructure in different sections; d) heat treatment; e) density; f) degree of elastic anisotropy; g) acoustic characteristics – rate of propagation of UZK, specific wave impedance, attenuation factor, coefficient of scattering, level of structural reverberation.

Characteristics of defect: a) type; b) dimensions; c) orientation with respect to direction of fiber of metal; d) orientation with respect to surfaces of article; e) orientation with respect to tensile stresses acting in further technological treatment and also in exploitation of article.

Only by study of the technology of manufacture of a controlled article, its macrostructure in different sections, state of surface, form and dimensions of article, acoustic characteristics of material, etc., is it possible to imagine clearly the character of defects subject to detection, their possible dimensions and orientation, the most probable zones of the resounded sections damaged by these defects. Having all these data, it is possible to develop a method ensuring the reliable detection of defects of a given type and the maximum volume of information about these defects.

Control operations are inherent elements of the technological process. Therefore where it is necessary one should anticipate special operations on preparation of surface of introduction of UZK or on removal of different flanges having technological value and subject to removal subsequently. Sometimes, it is even possible to introduce a special operation of heat treatment, promoting best "discovery" of certain defects and facilitating their detection.

In formulating the methodology in all cases when possible one should compare results of ultrasonic control with results of control of the same article (or templets specially cut from the article) by other nondestructive methods.

Without methodology prepared in this way it is possible to guarantee only detection of sufficiently big defects. Small and unfavorably oriented defects can be overlooked.

In formulating methodology the following parameters must be selected: a) frequency and power of UZK; b) type of UZK and direction of their introduction into article; c) type of acoustic contact; d) type of searching head; e) scanning diagram; f) sensitivity and tuning of flaw detector; g) mechanization and automation of control; h) indication and registration of flaw detector readings; i) methods

of interpreting the readings and determination of dimensions of revealed defects.

b. Selection of Frequency and Power of UZK

Frequency of UZK is chosen in accordance with the considerations used during the analysis of equation (58). For selection of optimum frequency ensuring highest sensitivity it is necessary to know dimensions of article and also attenuation factor and level of structural reverberation of material of article. Determination of dimensions is simple. The attenuation factor can be determined only very tentatively by tabular data in literature. In reality the attenuation factor can be considerably different not only for different alloys of one group but even for one alloy in different states of mechanical and heat treatment, and moreover — for different sections of one article. Therefore the attenuation factor should be determined directly on the controlled article in the resounded section. In industrial conditions such determination is complicated, inasmuch as flaw detectors of industrial type are not adjusted for measurement of the attenuation factor.

When the echo-flaw detector contains a calibrated attenuator, or if an attenuator is connected to the echo-flaw detector in the form of a special attachment, damping can be measured, for instance, by a method proposed by the author of [91], which involves comparison of amplitudes of echos from two equivalent control reflectors drilled directly into the controled article (Fig. 198), as far as possible in the zone subject to removal during further treatment and located at a different depth.

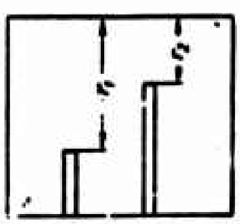

Fig. 198. Sample for determination of attenuation factor of UZK.

It is possible to measure damping in material of article more simply and exactly when there is a standard sample with known attenuation factor.

This requires only determination of the ratio "k" of amplitudes of bottom signals $U_{д.э}$ and $U_{д.и}$ during resounding of standard and article.

If thickness of standard — $B_э$, of article — $B = n \cdot B_э$, and damping accordingly is $\delta_э$ and δ, then

$$U_{д.э} = \frac{F}{B_э e^{2\delta_э B_э}} \text{ and } U_{д.и} = \frac{F}{B e^{2\delta B}}.$$

hence

$$\delta = \frac{1}{2B}\left(\ln\frac{k}{n} + 2\delta_э B_э\right), \tag{68}$$

and if $B = B_э$ (i.e., n = 1), then

$$\delta = \frac{1}{2B}\left(\ln k + 2\delta_э B\right). \tag{68a}$$

If attenuator is graduated in nepers, ln k is counted off directly on its scale and calculation becomes maximally simple. Such a method can sufficiently accurately determine the attenuation factor in blanks during the treatment of one face surface (surface of introduction of UZK) up to not less than $\nabla 6$, so that insignificant changes of acoustic contact during movement of searching head does not affect amplitude of echo.

Damping in the standard can be measured with high accuracy by the formula of A. A. Tukkayeva for immersion introduction of UZK.

$$\delta = \frac{1}{2B_э}\ln\left[\frac{U_п}{U_д}\,\frac{4\rho_ж c_ж\cdot\rho c}{(\rho_ж c_ж + \rho c)^2}\cdot\sqrt{\frac{1+\dfrac{16r_ж^2}{k_ж^2 a^4}}{1+\dfrac{16}{a^4}\left(\dfrac{r_ж}{k_ж}+\dfrac{B_э}{k_э}\right)^2}}\,\right]. \tag{69}$$

where $U_п$ and $U_д$ – amplitude of echos from front and bottom edges of standard, $k_ж$ and $k_э$ – wave numbers for water and material of standard, and remaining designations are the same as in Fig. 188.

Exactly as the attenuation factor, the level of structural reverberation should be determined directly in the resounded section of the controlled article. However, a simple and reliable method of determination of this level as yet does not exist, therefore when there is considerable structural reverberation optimum frequency of UZK must be chosen experimentally. Usually a frequency is selected at which echo from control reflector, located at maximum depth, with optimum relationship of amplification factor and magnitude of noise cutoff is clearly seen on screen of instrument.

It is necessary to note that this frequency can be so low that detection of defects whose dimensions not permissable by norms of rejection will be impossible.

If sensitivity threshold for a metal not possessing structural reverberation can be considered as a reflector with diameter equal to approximately one half-wavelength, when level of reverberation is considerable this limit shifts in the direction of an increase of diameters.

Curves in Fig. 194 and 196 describe the dependence of U_{ex} on 2b or S_0 at a zero level of structural reverberation. More correctly, this dependence should be shown by a family of curves for various levels of structural reverberation, as is schematically shown in Fig. 199.

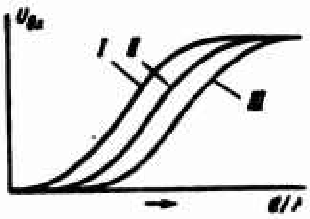

Fig. 199. Dependence of amplitude of echo on dimension of reflector for materials with different level I < II < III of structural reverberation.

From this figure it follows that the point of origin of the curve, i.e., maximum sensitivity, cannot be determined uniquely, since it is a function of a series of acoustic characteristics of the material.

Pulse power of UZK which must be introduced into the controlled article in order to ensure detection of a defect of given dimension at maximum depth also must be selected taking into consideration frequency of UZK, attenuation factor and overall size of the controlled article. On the basis of formulas recorded during the derivation of equation (58) it is possible, taking as constant all terms except frequency, amplitude of voltage exciting the pulse, and depth of bedding of defect, to write an expression for optimum intensity of UZK attaining surface of defect:

$$I_{\text{опт}} = M\frac{U^2 f^2 e^{-2\delta r}}{r^2} \qquad (70)$$

(here the same simplifications are made as in deriving expressions for determination of the attenuation factor).

It follows from this that with increase of depth of bedding of defect it is necessary to increase proportionally amplitude of voltage exciting the pulse. Regarding frequency dependence of amplitude of this voltage, it is sufficiently complicated, inasmuch as it is determined by the product $f^2 \cdot e^{-2\delta r}$.

In industrial echo-flaw detectors there is usually no adjustment of voltage exciting the pulse, pulse power of UZK in certain limits is regulated only by changing the length of the exciting pulse, which affects resolving power and changes magnitude of dead band.

Introduction of adjustment of amplitude permitted a more correct selection of pulse power.

It is necessary to say that in the practice of flaw detection this frequently is not given the proper value. Articles of average overall dimensions made of materials with small attenuation factor are controlled at a knowingly excess power in the pulse; due to this it is necessary to decrease maximally the amplification factor of the flaw detector.

At the same time, large scale articles are sometimes controlled at insufficient power, when even during maximum amplification the bottom echo not is revealed. Frequently the article is controlled successively from two sides, considering that such a method ensures full reliability of control. Meanwhile, there are no bases for an affirmation. Damping of UZK in the article can be so great that amplitude of echo from a defect lying at half the depth will be insufficient for its detection.

This once again confirms necessity of anticipating in flaw detectors possibility of adjustment of amplitude of voltage exciting the pulse in sufficiently wide limits.

c. Selection of Type of Ultrasonic Waves and Methods of Reduction of Dead Band

Selection of type of ultrasonic waves is dictated by dimensions of article and character of defects. Thin-walled articles are usually controlled using normal waves. In the control of articles of average and big cross sections longitudinal, shear, surface waves can be used.

Most frequently longitudinal waves are used, which are usually introduced along the normal to the surface of the article in order to ensure best conditions of reflection from defects oriented in the plane parallel to the surface of introduction of UZK.

However, if the part is bounded by unparallel surfaces, or if in a part of complicated form a defect is oriented in the direction of the fiber not parallel to surface of introduction of UZK; the beam should be directed not along the normal to this surface but at a certain angle to the normal calculated

so that after refraction it is oriented perpendicularly to surface of defect.

In using longitudinal waves mostly it is necessary to be concerned with the existence of a temporary dead band.

A temporary dead band, constituting an uncontrollable layer in which the echo from a defect is not resolved from the sounding pulse – is a serious fundamental deficiency of the echo-method. This deficiency is a result of limitation of resolving power of the method, which is one of the most important characteristics of the contemporary ultrasonic echo-flaw detector. By resolving power of the method is understood the ability to receive separately and to produce distinctly (with help of indicator) echos from two and more reflectors located close to one another in direction of propagation of pulse of ultrasonic oscillations.

Resolving power is determined by duration of sounding pulse ($\tau_{и}$), duration[1] of transition processes ($\tau_{п}$) and rate of propagation (c) of elastic oscillations in material of controlled article. Measure of resolving power is minimum resolved distance.

Designating this distance by l_{min} for a square pulse, in accordance with expression (61) duration $\tau_{и}$ = 2 μs, duration of transition process $\tau_{п}$ = 3 μs, and rate of propagation of ultrasonics in steel c = 6,000 m/s, we obtain

$$l_{min} = \frac{6\cdot 5}{2} = 15 \text{ мм.}$$

Limitation of resolving power makes impossible separate observation of defects located close to another – a "dead band" appears. This forces considerable allowances to treatment of article and consequently increases manufacturing cost of article.

In contemporary echo-flaw detectors during work on "average" frequencies of the order of 2-5 MHz the dead band is usually 5-10 mm. In a number of cases in the control of important articles or blanks not having a sufficiently large allowance for treatment, such a large dead band makes control insufficiently reliable. Naturally, reduction of this zone is possible only by decreasing duration of sounding pulse and transition processes.

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[1]By duration of transition processes, here and in the future is conditionally understood the time after which amplitude of oscillations drops to a given value, for instance to 0.01 of the initial value.

Resolving power can be increased by using not square but bell-shaped pulses, or, which is considerably better, pulses of exponential form. Steepness of leading front of an exponential pulse permits obtaining high accuracy of distance reading on the scale. When two exponential pulses are close together on the screen they are better resolved than square pulses. Duration of exponential pulse can be easily made sufficiently small, which promotes an increase of resolving power.

It is necessary, however, to remember that reduction of pulse duration can lead to decrease of sensitivity. This is connected with the fact that in oscillatory systems with a sufficiently high quality factor oscillations grow gradually, attaining maximum amplitude not at once but only after a certain time ("time of establishment") after beginning of process. This causes gradual distortion of form and increase of duration of pulses in the receiving-amplifying channel (pulse of exponential form gradually is turned into a bell-shaped pulse).

Distortion of form of pulse — increase of its duration can occur also during reflection from surface of defect. If duration of sounding pulse is designated by $\tau_{\text{и}}$, rate of propagation of UZK — c, distance from radiator to the nearest point of reflecting surface — r, extent of this surface in direction of resounding — z, then the "run" time t_1 of the leading edge of a pulse of UZK to the nearest point of the reflecting surface and back is (Fig. 200):

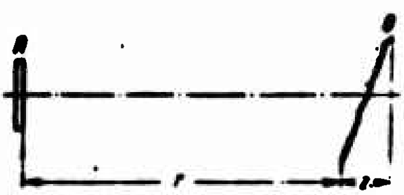

Fig. 200. Pulse spreading during reflection from a defect oriented perpendicularly to beam: n — piezoconverter; 0 — defect.

$$t_1 = 2\frac{r}{c}.$$

The trailing edge of the pulse will attain the most remote point of the surface of the reflector in time interval:

$$t_2 = \tau_{\text{и}} + 2\frac{r}{c} + 2\frac{z}{c}.$$

Consequently, duration of reflected pulse (echo) is

$$\tau_{\text{э}} = t_2 - t_1 = \tau_{\text{и}} + 2\frac{z}{c}.$$

This, only upon reflection from a flat surface oriented perpendicularly to

beams, i.e., when $z = 0$, does pulse duration not change[1] (for instance duration of bottom echo). In all remaining cases it increases. Comparing duration of echo from defect with duration of bottom echo a certain idea can be obtained about form and orientation of surface of revealed defect. For instance, if duration of sounding pulse is $\tau_и = 2$ μs, extent of the reflecting surface in metal (aluminum, steel) is 6 mm, then duration of echo will twice exceed duration of bottom pulse. This naturally lowers the resolving power. What has been shows necessity of decreasing duration of sounding pulse.

To achieve this in all contemporary domestic and foreign echo-flaw detectors (as was noted above) mechanical damping of piezoelement of searching head is used. The piezoelement is glued to a massive damper made of a material with large attenuation factor of ultrasonics. A sufficiently rigid bond with the damper results in the fact that after cessation of action of exciting pulse to the piezoelement free oscillations of the latter comparatively rapidly fade (i.e., the quantity $\tau_н$ – see Fig. 201a and b).

Such damping has, however, serious a deficiency; due to the large damping the quality factor of the system is very low and amplitude of oscillations of piezoelement is very small. If, however, by conditions of resounding it is necessary to increase pulse power of ultraonics, it is necessary to increase considerably voltage of the high-frequency pulse exciting the piezoelement. However, as is easy to see, along with growth of amplitude of oscillations duration of transition processes is increased also during which voltage drops to the given value.

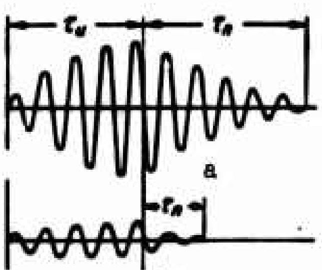

Fig. 201. Oscillations of piezoelement: a) undamped; b) damped.

Deficiencies of the conventional system of damping should also include disturbance of the cophasal quality of oscillations of separate sections of surface of piezoelement, leading to distortion of wave field and to lowering effectiveness of radiation; besides there are many difficulties connected with correct selection of material of damper.

[1]If curvature of wave front is disregarded.

It is necessary to note also that in attempting to decrease pulse duration in recent years very high frequencies (up to 25 MHz) have begun to be used. This, however, is not always advisable since damping of ultrasonics sharply increases, level of structural reverberation is increased, and introduction of ultrasonics into metal is hampered. At the same time necessary sensitivity is practically ensured usually at frequencies near 4-5 MHz.

Everything said verifies that mechanical damping of piezoelement is not, and cannot be a rational system making it possible to obtain a short pulse of elastic oscillations of sufficient power, including at high frequencies.

Mechanical damping is faulty in principle. During mechanical damping into the oscillatory system is introduced very strong damping and therefore the system constantly possesses a low quality factor. Meanwhile in the beginning of excitation of oscillations, i.e., prior to achievement of necessary amplitude it would be desirable to have a large quality factor, and only after that, i.e., when pulse has already formed, then damp the system compensate its oscillation.

The author and B. G. Golodayev developed[1] a method of obtaining of pulses of elastic oscillations of different duration and different power, including very short and sufficiently powerful, in a wide range of frequencies based on electrical compensation of oscillations of piezoelement selective in time in the radiation regime.

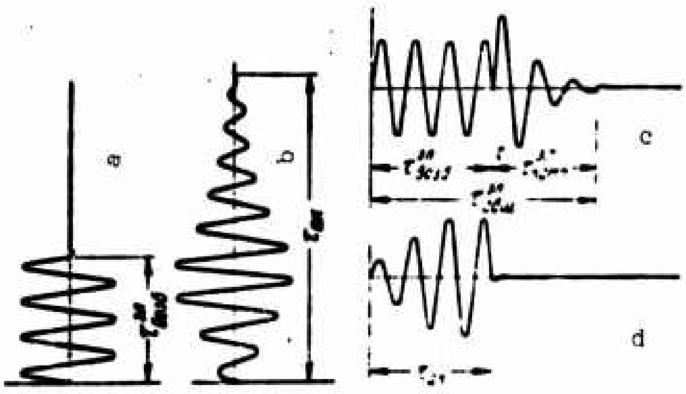

Fig. 202. Obtaining short pulses of UZK: a) electrical exciting pulse; b) pulse of UZK; c) electrical pulse with compensation; d) short pulse of UZK.

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[1]D. S. Shrayber, B. G. Golodayev. Author's certificate No. 125935. SSSR, 1959.

Essence of the method is explained in Fig. 202. The exciting pulse (Fig. 202a) from a high frequency oscillator puts into oscillator motion (Fig. 202b) the piezoelement. If at time t after the exciting pulse a compensating pulse goes to the piezoelement (Fig. 202c) of corresponding amplitude and form, acting on the piezoelement in antiphase to the oscillations, as a result of superposition of oscillations caused by both pulses oscillations of piezoelement will cease (Fig. 202d) since starting from time t both oscillations are in antiphase and attenuating by identical law and therefore cancel each other. By changing amplitude and moment of supply of compensating pulse to oscillating piezoelement it is possible to regulate duration of radiated pulse of elastic oscillations in wide limits.

Figure 203a gives photography from the screen of an oscilloscope depicting the acoustic pulse radiated into water by an undamped quartz plate 25 mm in diameter and 1.9 mm thick (f = 1.5 MHz). The plate was excited "percussively;" reception was carried out by a damped quartz plate 25 mm in diameter 0.1' mm thick (f = 17 MHz). Therefore during reception, resonance phenomena and connected distortions of form of the received pulses were absent.

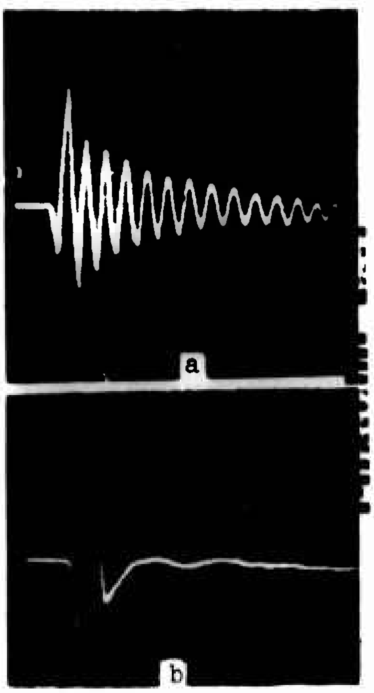

Fig. 203. Pulse of UZK radiated into water by an undamped quartz plate, without compensation – a and with compensation of oscillations – b.

The pulse shown in Fig. 203b is obtained by the method of electrical compensation. In this case free oscillations of piezoelement are compensated and form of resultant acoustic pulse is close to theoretical; its duration is around one half-period.

Use of a short pulse in conditions of ultrasonic flaw detection, besides decrease of dead band, are also interestingly because with decrease of pulse duration frequency spectrum of radiated oscillations is expanded. This leads to a weakening of interference phenomena observed in the near zone of the radiator and with a maximally short pulse one half period in duration – to a monotonic dependence

of amplitude of echo on distance to defect and to a decrease of irregularity of intensity of UZK within limits of solid angle of diagram of directivity, which essentially facilitates determination of dimensions of revealed defect.

The searching head design when electrical compensation of oscillations is used is significantly simplified and exploitational characteristics are essentially improved.

The dead band in work by the contact echo-method can be reduced to a minimum, which is very important in a wide interval of frequencies. This opens large prospects for ultrasonic control of articles from materials with large damping of ultrasonics and with high level of structural reverberation (for instance heat-resistant alloys).

As was already indicated, control of such articles is possible only on "low" frequencies (0.5-1.5 MHz). However, practically such control has not been used, mainly due to the excessively large dead band during work by a combined searcher with mechanical damping of piezoelement. Electrical compensation of oscillations permits obtaining a small dead band also on low frequencies.

Especially interesting possibilities appear during work by the immersion echo-method. In this case the dead band is determined by duration of echo from front edge, which on screen of instrument is seen separately from the sounding pulse and echo from front edge, and consequently decreases the dead band. There is, however, a possibility of absolutely liquidating the dead zone by means of acoustic compensation of oscillations of piezoelement in conditions of reception during excitation by echo from front edge of controlled article. The essence of this method is explained in Fig. 204. Oscillations of piezoelement – П, placed in water, are excited by a high-frequency pulse with application of electrical compensation (above method) or without it. Pulses of elastic oscillations are radiated, moreover, into both sides. Sounding pulse З propagates in the direction of the controlled article – И, is reflected from front edge and in the form of an echo returns to piezoelement, forcing the piezoelement to oscillate. Compensating pulse K propagates in the opposite direction, encounters

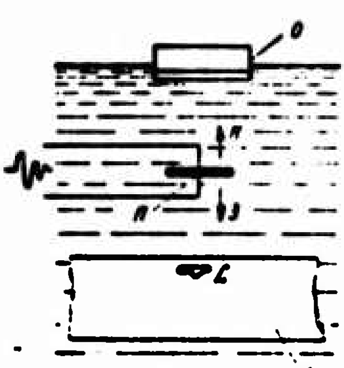

Fig. 204. Diagram of acoustic compensation of oscillations.

reflector O located in water at the same distance from the piezoelement as the controlled article, and made, for instance, in the form of a disk one half-wave thick from a material suitable in acoustic characteristics. The other side of the reflector touches the air. Reflection of pulse of elastic oscillations from surface of reflector will occur just as from the water – air interface, i.e., with loss of half-wave.

The reflected compensating pulse will reach the piezoelement simultaneously with the echo from the front edge of the article, but in antiphase with respect to it. Arrival time of compensating pulse is regulated by change of distance between piezoelement and reflector, and amplitude is regulated with the help of a special diaphragm in the head shown in Fig. 205.

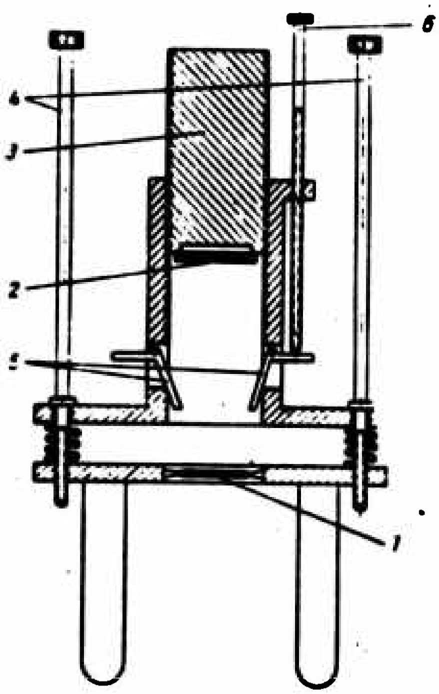

Fig. 205. Structural diagram of searching head with acoustic compensation of UZK: 1 – piezoelement; 2 – reflector; 3, 4 – screws regulating distance between piezoelement and reflector; 5 – diaphragm; 6 – screw regulating opening of diaphragm.

If sounding and compensating pulses are equal in amplitude, they mutually compensate one another and piezoelement will not oscillate. At the same time, from any defect Д, (no matter how close to front edge of article) if in dimensions it satisfies conditions of revealability an echo will be reflected, exciting oscillation of piezoelement, clearly observed on screen of instrument.

An experimental check completely confirmed these considerations. Figure 206a is the photography from the screen of an echo-flaw detector during resounding of a sample with control reflector on a frequency of 1.5 MHz. On the left part of the screen is seen the sounding pulse, in the middle – reflection from front edge of sample, on the right – compensating pulse reflected from reflector (distance from reflector to piezoelement is more than distance between piezoelement and front edge of sample). With approach of reflector to piezoelement the compensating pulse shifts on the screen to the left and at coincidence of distances between piezoelement and front edge of sample on one side and reflector – on the other compensation of oscillations occurs as a result of which the pulse

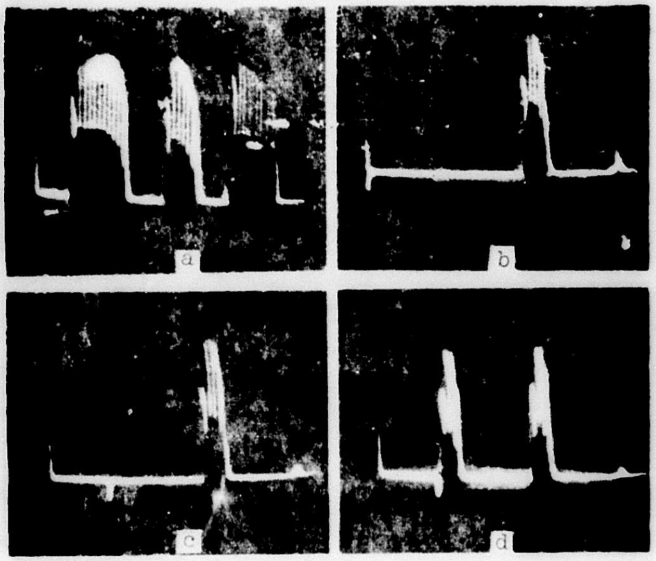

Fig. 206. Image on screen of immersion echo-flaw detector, using a compensation circuit for UZK reflected from the front surface.

reflected from the front edge of the sample completely disappears and on the screen in this place only the time axis is seen (Fig. 206b). Inasmuch as the experiment was conducted on the V4-7I, to mark points corresponding to front edge of sample the time axis it was convenient to use a mobile, accurate depth meter (Fig. 206c).

After such tuning of the radiator which ensures full compensation of oscillations, the head was moved on its supports along the flat surface of the sample. Figure 206d shows moment of detection of a control reflector 6 mm in diameter, located 0.4 mm under surface of introduction of UZK.

There are no bases to doubt that reflection could be obtained from a reflector of smaller dimensions located less than 0.4 mm deep, if in the investigated sample such a reflector could be made.

The dead band with this method of compensation is practically zero. However, such a method has essential limitations. The basic limitation is necessity of exact conformity of distances between radiator and surface of article on one side and radiator and reflector on the other. This condition is necessary in order to ensure simultaneous income of pulses reflected from front surface and compensating pulses. It can be carried out only when the surface of the controlled

article along which slides the searching head mounted on rigid legs is flat and thoroughly finished. For full compensation of these pulses their amplitudes must be equal.

Construction of searching head, as was shown above, permits exact regulation of distance between radiator and reflector and also partial diaphragming of reflector, and thus, full compensation of oscillations. However, if we tune a motionless head to full compensation and then move it along the surface of the article, compensation can be disturbed due to a change of pulse amplitude reflected from front surface of article. This change for a sufficiently treated surface usually is the result of instability of acoustic contact due to unequal conditions of wetting of surface in different points. Addition of superficially active material (emulsifier [OP-7] (ОП-7), 0.3-0.5 percent by weight) to water liquidates this instability and compensation is kept during movement of searching head.

The most effective turned out to be use of compensation of electrical oscillations directly on receiving-amplifying channel input after the proposition of the author and B. G. Golodayev[1], which provides a separation of a pulse into two with relative shift of a half-period and with subsequent composition. Composition gives voltage pulse equal to half the period of free oscillations of the piezoelement.

If in the controlled article at a small depth under the surface is a disturbance of continuity (defect), the echo from it also will be separated on resistor R and will be clearly observed on screen of indicator under the condition that its delay with respect to reflection from front edge will be more than half the period of free oscillations of the piezoelement. Thus extent of dead band will be not more than half the period of free oscillations of piezoelement, and at a frequency of 1.5 MHz is ≈1 mm in steel or an aluminum alloy.

It is possible to think of other methods of realizating proposed methods of electrical and acoustical compensation of oscillations of a piezoelement which have insignificant distinctions and possess both advantages and disadvantages.

These methods cannot be considered finally developed, however undoubtedly their further development will allow essential improvement of the most important

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[1]D. S. Shrayber, B. G. Golodayev. Author's certificate No. 148949, USSR, 1961.

characteristics of ultrasonic echo-flaw detector [230].

We considered in detail the question about a temporary dead band as applied to control with the help of longitudinal UZK. This question has smaller value for control by shear and surface UZK.

Shear UZK are used for detection of defects oriented in planes not parallel to surface of introduction of UZK. It is very convenient, for instance with the help of shear UZK, to quality control welded seams with different butting angles.

However the limitation of shear UZK to only control of welded joints does not follow. It is possible to name a number of examples of effective control of other articles with corresponding orientation of defects. For instance, in large scale forgings of square cross section, frequently cracks oriented along the diagonal of the square are met; in a stamping of complicated form metallurgical defects oriented in the direction of the fiber in specific zones where the fiber is bent can be oriented so that longitudinal UZK introduced along the normal to the surface of the article cannot be reflected in the direction of the searching head.

During preparation of the method of control one should consider all sections of the article having defects and orientation of these defects, and also outline zone of control with use of longitudinal and shear UZK so that control covers the whole cross section of the article. If we are limited to some longitudinal UZK, separate sections of the cross section can remain unresounded due to the complexity of form of the article (geometric dead bands).

The use of shear UZK for control has one more interesting peculiarity explained by the fact that shear oscillations are polarized.

As follows from what was given in Table 3 for values of quantities determining conditions of propagation of UZK, these conditions in a polycrystalline medium are more favorable for shear waves than for longitudinal. This provides a basis to assume that the level of interferences from structural reverberation during the control of macrocrystalline metal can be lowered with the use of polarized shear UZK.

In the usual method of excitation of shear UZK in metal by means of transformation of longitudinal UZK radiated by the piezoelement as they pass

from body of searching head through layer of contact lubricant into metal, polarization of shear UZK is very insignificant.

However, if we use a shear wave with maximum degree of polarization, real sensitivity of the method in conditions of work with metal possessing high level of structural reverberation can be considerably increased. This can be affirmed on the basis of investigation of peculiarities of behavior of polarized shear waves under different conditions of reflection from the interface of two media.

The first investigation of polarized shear UZK was published by Firestone and Frederick [231]. They established the rotation of the plane of polarization of UZK during reflection from mirror interface of two media.

The investigation of the author and Z. I. Manayeva [232] established the dependence of intensity of longitudinal UZK going from a solid body into liquid on angle between plane of incidence and plane of polarization of shear UZK incident from the solid body to this boundary. With increase of angle between plane of polarization of shear UZK and plane of their fall from 0 to 90°, amplitude of longitudinal oscillations drops 2-2.5 times (Fig. 207).

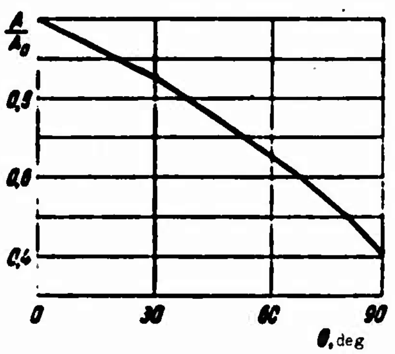


Fig. 207. Dependence of amplitude of longitudinal UZK in water on angle between plane of polarization and plane of incidence of shear UZK onto metal - water interface.

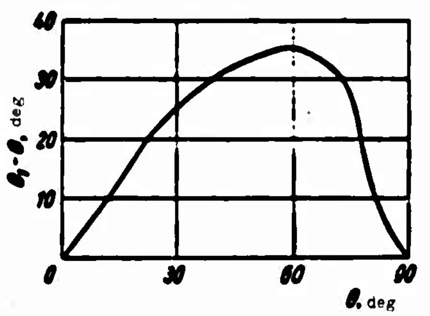


Fig. 208. Rotation of plane of polarization of reflected UZK depending upon angle of rotation θ of plane of polarization of incident UZK.

The same investigation determined angles of rotation of plane of polarization of reflected shear wave with respect to incident waves as a function of angle of rotation of plane of polarization of the incident wave. It turned out that when angles of rotation of plane of polarization of incident wave are from

30 to 60° rotation of plane of polarization of reflected wave attains maximum values (Fig. 208). During propagation of shear UZK the plane of polarization of beams repeatedly reflected from edges of metal crystallites and returning to point of introduction of UZK in the form of noises of structural reverberation, therefore as a rule will not coincide with the plane of polarization of UZK introduced into metal and longitudinal UZK excited by these noises in the layer of contact liquid and then in the body of the searching head will be weakened. Therefore the echo from the heterogeneity toward which the searching head is aimed (if we consider that the reflecting surface of this heterogeneity is perpendicular to the axis of the beam of UZK) will be received by the piezoconverter with considerable advantage as compared to reverberational noises constituting oscillation polarized in other planes. As a result of this the ratio of level of useful signal to level of interferences will be increases and actual sensitivity of method will increase.

Everything said occurs if shear UZK possess linear polarization. However, in conditions of obtaining shear oscillations from longitudinal, as occurs in the use of a refracting head of plastic, polarization for the most part is circular and elliptic. Approach to linear polarization is possible if we reject obtaining shear UZK from longitudinal by transformation, and cross to radiation of them with the help of a quartz plate of Y-cut (if we use optical analogies, the role of the plate is that of polarizer) with introduction of shear oscillations into the controlled article and obtaining a polarized echo with reception by the same (or a series) oriented plate of Y-cut (analyzer) located correspondingly.

Realization of such a method is connected, however, with essential difficulties, inasmuch as shear oscillations vertually do not propagate in the liquids usually used for acoustic contact, and therefore their effective transmission from body to head into controlled article through liquid acoustic contact is impossible. If it is necessary to introduce shear UZK into metal, usually a quartz plate of Y-cut is glued to the surface of the controlled article. Salol gives satisfactory results. It is possible also to use a mixture of cedar oil with acetone. Gluing of plates naturally is unacceptable for use in defectoscopy requiring mobile acoustic contact. Samples with glued plates of Y-cut in laboratory conditions can nonetheless be used to confirm advantages of work on shear UZK.

A radical solution of problem of introduction of shear UZK which allows their use for control in industrial conditions is possible, if instead of introducing a beam in a direction normal to the surface we introduce it at a certain angle α to this normal[1].

The diagram on Fig. 209 explains the essence of the method proposed by the author. Let us assume that I and III are two solid media (for simplicity, we will consider them identical, for instance – steel), and II is a liquid layer playing the role of acoustic contact. Let us take rate of propagation of longitudinal UZK in steel $c_L^I = c_L^{III} = 6000$ m/s, in liquid $c_L^{II} = 1500$ m/s, and of transverse UZK in steel $c_S^I = c_S^{III} = 3250$ m/s. Let us imagine that from liquid II into medium III at angle β to the normal (beam L_{II}) longitudinal UZK are incident. Then, as is known, in the liquid will be observed beam L'_{II} – longitudinal UZK, reflected under the same angle, and in medium III there will be in general two beams: L_{III} longitudinal UZK and S_{III} – transverse UZK. If angle β is selected from calculation

$$\beta = \arcsin \frac{c_L^{II}}{c_L^{II}},$$

which corresponds to $\beta \approx 14$ degrees, beam L_{III} will slide along the interface of II and III, as was shown by the dotted line (L'_{III}). Thus when $\beta \geqslant 14$ degrees, in medium III will be one beam S_{III} (shear UZK) directed at angle α to the normal, where α is determined from the relationship

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_s^I}{c_L} = 2.16$$

and consequently at $\beta = 14^\circ$ angle $\alpha = 33^\circ$, and with increase of β angle α grows.

We assume that from medium I into medium II shear UZK are incident at an angle $\geqslant 33$ degrees (beam S_1). Then in medium I will appear two reflected beams S'_I and L'_I (shear and, correspondingly, longitudinal UZK), and in medium II – one beam L_{II} (longitudinal UZK), directed at an angle $\beta \geqslant 14$ degrees.

Thus, using transformation of Shear UZK into longitudinal and back, it is possible, transmitting shear UZK from medium I at a certain angle, to introduce

[1]D. S. Shrayber. Author's certificate No. 122932 USSR, 1957.

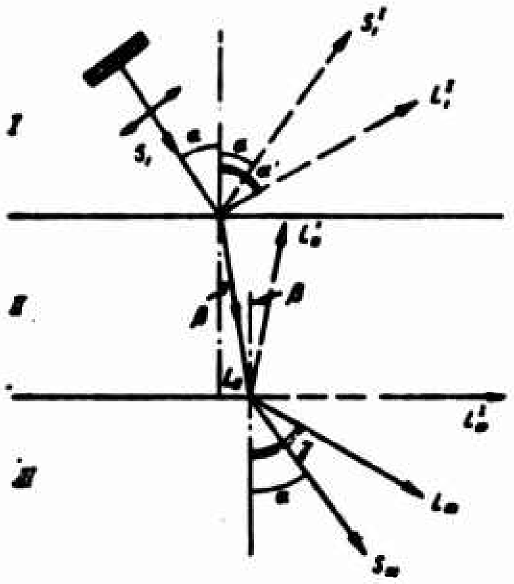


Fig. 209. Transmission of shear UZK from one solid medium into another through liquid contact with use of double transformation of UZK: s_{I} – incident shear UZK; l_{II} – longitudinal UZK excited in liquid medium; s_{III} – shear UZK excited in solid medium.

then into medium III at the same angle. These considerations were checked experimentally and were completely confirmed. The results open the most interesting prospects. First, a searching head for work by shear waves cannot be plastic, as has been accepted, but metal, which sharply increases resistance to wear of heads. Secondly, and not less important, in the control of articles from metal with a high level of structural reverberation, shear UZK, polarized in the principal plane and incident along normal to surface of defect, will be received by the piezoconverter with a considerable advantage over reverberational noises because plane of polarization of noises, due to its rotation when there are flutter echoes from crystallites of metal, does not coincide with principal plane of polarization. This phenomenon, observed in conditions of laboratory experiment and required in a thorough check in practical conditions, permits outlining a way to increase the ratio of useful signal to reverberational noises in the control of metal with high level of structural reverberation, i.e., increase real sensitivity of method in a number of cases, for instance, during control of welded joints of large scale forgings, etc.

To the earlier conclusion concerning expediency of combination of control by longitudinal and shear UZK to increase fullness of control, one should add the following. During control of half-finished products and articles not having allowances, technological treatment of which could lead to appearance of surface defects (for instance, tempering cracks) it is expediently also to use surface (Rayleigh) UZK, making it possible to reveal very thin surface cracks, frequently in very difficultly accessible places. It is clear that using surface waves in the control of half-finished products having a significant allowance which is removed during further treatment is inexpedient.

Surface waves only in recent years have been used in defectoscopy. Uniqueness of laws of propagation of these waves makes their use very promising for a number of problems not solved by usual methods.

The basic feature of Rayleigh waves is that with increase of depth their amplitude rapidly drops by exponential law. A Rayleigh wave is a combination of longitudinal and shear nonuniform waves attenuating with a different rate with increase of depth (a longitudinal wave attenuates faster than a shear wave). Rates of propagation of these waves along surfaces are identical and are equal to phase speed of propagation of a Rayleigh wave, which for the majority of metals is ~90% rate of propagation of a shear wave. A Rayleigh wave is localized in a thin surface layer one-two wavelengths thick. At a depth exceeding the shown magnitude oscillations are practically absent. Along the free surface of an elastic medium a Rayleigh wave propagates with small damping, rounding all parts of relief. Particles of the surface move along ellipses (Fig. 210) whose major axis is oriented along the normal to surface, and whose minor axis is in the direction of propagation of the wave [234, 235]. With increase of depth both axes of the ellipse decrease at a different rate, eccentricity of ellipse increases and gradually degenerates into a straight line, indicating the presence of some shear oscillations.

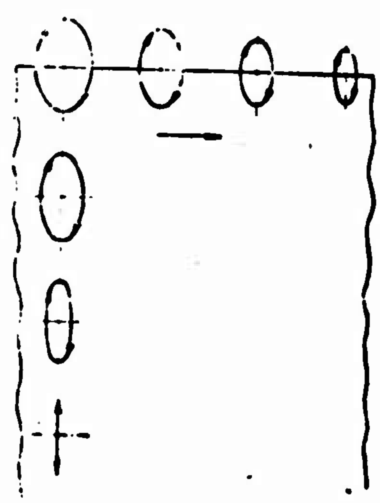


Fig. 210. Oscillations of particles of a solid medium during propagation of surface waves.

From what has been said can be made the conclusion that in forming a Rayleigh wave a basic role is played by shear oscillations, the role of longitudinal oscillations is considerably less. If this is so, obviously it is more profitable to excite surface waves by means of transformation of shear, and not longitudinal oscillations.

By calculation it is easy to estimate the ratio of amplitudes of shear components of a Rayleigh wave excited by transformation of shear and longitudinal oscillations. It is ≈ 10—15 [232].

On the basis of these considerations, N. V. Babkin prepared brass searching heads with piezoelements in the form of quartz plates of Y-cut for work by Rayleigh

waves. Sensitivity of these heads turned out to be very high, considerably exceeding sensitivity of plastic heads. An advantage of a brass head is also high resistance to wear and reliable electrical shielding.

Angle of incidence of shear UZK in a brass head for control of steel articles in accordance with calculation was selected as 47°, which ensured satisfactory of its work. However, for control of articles from other metals with another rate of propagation of Rayleigh waves, possibly another angle is needed. In connection with this the amplitude of a Rayleigh wave reflected from an obstacle at a certain deviation of the angle of incidence from that calculated was measured. Measurement showed that deviation of the angle of incidence from that calculated value within the limits of ± 3 degrees leads to weakening of echo by 2.5-4 dB, which corresponds to a relative weakening by 25-30%. This indicates the expediency of adjustment of angle of incidence for the purpose of selection of an optimum value, although it confirms the absence of its sharp criticality.

Creation of a searching head with adjustable angle of incidence of shear UZK and with a constant point of introduction into a controlled article is very complicated; a solution is possible using the above principle of double transformation of UZK.

Such all-purpose metallic heads with alternate angle of incidence, radiating shear and Rayleigh waves and possessing high operational indices indisputably will have essential advantages as compared to plastic heads presently used. In making these heads from metal more difficulty is met: as compared to plastic the small attenuation factor of UZK in metal does not permit using the usual "trap" for extinguishing UZK repeatedly reflected from edges of body of head. Experiments have showed that interference of these UZK can be effectively lowered by means of application of hemispheric scatters cut on the edge of the body of the head with correct selection of ratio of their diameter to wavelength λ in body of head. Thus, when diameter of scatterer is 2λ, reduction of the level of interferences was near 20 dB. If cavity of scatterers is filled with a material with high attenuation factor (for instance, compound masses), the level of interferences will be lowered still more. Broad prospects in creation of heads using shear UZK appeared in connection with development of synthetic liquids allowing sufficiently effective transmission of shear oscillations.

d. Direction of Resounding. False Echos and Methods of Their Interpretation

After selection of type of UZK utilized in the control of a given article, from a drawing and still better from templets cut from different sections of article it is necessary to outline direction of resounding of every section by different types of UZK in order to minimize presence of geometric dead bands and to determine which possible radar echos can be seen on the screen at different positions of searching head.

Selection of direction of resounding will be correct if it ensures optimum conditions of reflection of UZK from surface of defect. Only in the simplest case, in the control of an article with flat and parallel surfaces and when defects are oriented parallel to these surfaces, will the direction of resounding coincide with the normal to the surface of the article, and on the screen of the echo-flaw detector will the picture shown in Fig. 155 be observed. Frequently, however, during control of articles of more complicated form, to guarantee optimum reflection of UZK from a defect the beam must not be directed along the normal. In this case the picture on the screen can differ from that shown in Fig. 155.

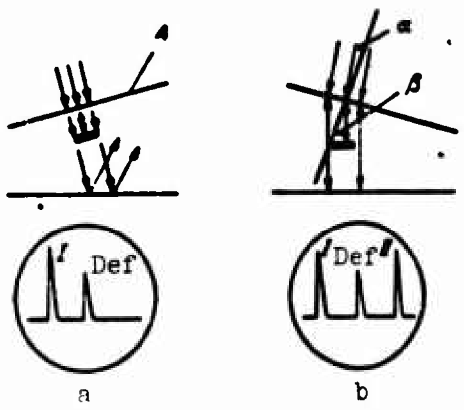


Fig. 211. Different methods of introduction of UZK in the control of articles with nonparallel flat surfaces: a — without refraction; b — with refraction; I — initial signal, II — bottom signal.

For instance, if flat surfaces of the controlled article are not parallel to one another, and the defect is oriented in the plane parallel to one of these surfaces, control can be either according to the diagram of Fig. 211a, by means of introduction of UZK along the normal to surface A (and to the defect) — on the screen in certain cases the bottom signal will not be seen — or according to Fig. 211b at an angle to the normal ensuring as a result of refraction a perpendicular fall of UZK on the surface of the defect and on the bottom surface of the article.

Still more complicated is control of articles bounded by curved surfaces. For instance, during control of thick walled cylindrical blanks by the immersion echo method orientation of axis of radiator along the normal to the surface of the cylinder is insufficient. Divergence of beam of UZK in water, different length of path of various beams in water, different angles of incidence of these beams on surface of cylinder, and

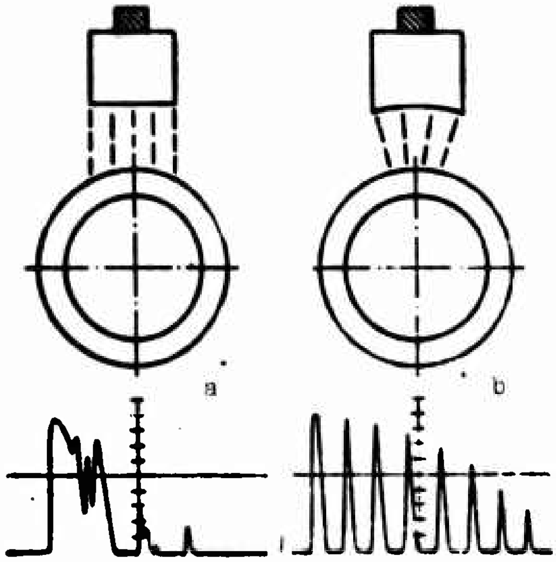


Fig. 212. Conditions of reflection of UZK from internal surface of a pipe during control with a searching head with flat — a and concave — b radiating surfaces.

different angles of refraction in wall of cylinder create a complicated picture of reflection of UZK from internal surface of cylinder and lead to distortion of picture on screen (Fig. 212a). If, however, the radiating surface is in accordance with curvature of article (using an intermediate lens or bent crystal), it is possible to direct all beams along the normal to the surface of the cylinder. In this case on the screen will be seen evenly located radar echos from the internal surface (Fig. 212b).

In a number of cases in the control of articles on the screen can be observed signals which are not echos from defects and are usually called false.

Therefore in composing methodology of control it is important to predetermine what picture should be observed on the screen for different positions of the searching head, what spurious signals will be seen and the cause of their appearance.

Spurious signals on the screen of the echo-flaw detector can be observed during control of blanks of simple form, and especially during control of different half-finished products and articles of sufficiently complicated form. They complicate the picture observed on the screen of the echo-flaw detector, can be the cause of incorrect interpretation and consequently an incorrect quality judgment.

During control by the pulse echo method of different articles of simple form with sufficiently large transverse dimensions of the resounded section, on the flaw detector screen usually a sounding pulse is seen on the left, on the right a bottom echo, and between them the horizontal time axis. Appearance of vertical peaked traces (peaks) on the scan between sounding pulse and bottom echo indicates a heterogeneity in the controlled article causing reflection of UZK.

In real conditions, however, frequently even during control of articles of simple form a more complicated picture is observed: along with the above signals other echos of different origin may be seen, sometimes essentially distorting the instrument readings and hampering their interpretation. For a complete

interpretation of instrument readings the origin of every echo should be explained.

The appearance of various kinds of "false" echos is determined mainly by the geometry of propagation of ultrasonic oscillations in the controlled article and transformation of these oscillations during reflection from various kinds of recesses, grooves, hollows, holes, and other reflecting surfaces.

False echos, depending upon conditions of their formation can be received by the searching head in different intervals of time after the sounding pulse is sent, and in accordance with this can be observed either prior to (more to the left) the first bottom echo, after it (to the right), or (in a particular case) simultaneously with the first bottom echo, merging with it on the instrument screen.

It is considered that false echos observed after the first bottom echo do not distort instrument readings and need not be considered during interpretation. So that the attention of the operator is not distracted by the appearance of these echos during control of articles of constant thickness, in certain instruments (for instance, the [V4-7I] (B4-7И)) the sweep length is regulated so that the end coincides with termination of bottom signal.

However, as will be shown below, false echos observed to the right of the bottom signal, essentially distorting the instrument readings, permit obtaining additional information, and therefore in a number of cases they must be considered.

Let us consider several examples of such echos.

Let us assume that the controlled article has the form of a right angle parallelepiped, on one edge which (in this example the "bottom" edge) is a shallow groove of right angle cross section (Fig. 213a).

Searching head И sends into the article longitudinal UZK in the form of a divergent beam. As the searching head advances in the direction shown by the arrow, the primary beam is reflected from the bottom edge or from the surface of the groove in direction КИ and on the screen of the flaw detector is seen the botton echo ДС. Depth of groove is small, therefore insignificant displacement of bottom echo during passage of searching head above groove can remain unnoticed if "normal" position of bottom echo was not preliminarily fixed, as can be done, for instance, in the V4-7I with the movable mark of a depth meter. If in the controlled article there is no heterogeneity causing reflection of UZK, no echos to the left of the bottom echo can be seen on the screen. However, lateral beams, leaving the radiator at different angles within limits of solid angle of directivity, can,

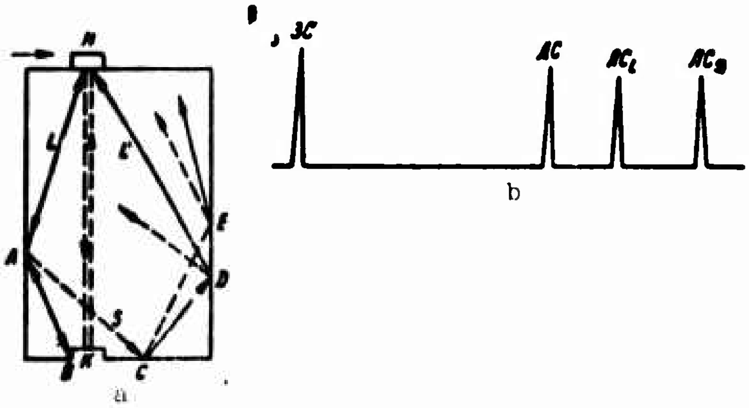


Fig. 213. Conditions of appearance of false echos as a result of reflection of UZK from lateral surfaces of article: a – diagram of propagation of UZK; b – image on screen; ЗС – sounding signal, ДС – bottom echo. ЛС$_L$ and ЛС$_S$ – false echos observed as a result of reflection of longitudinal UZK and also as a result of their transformation into shear oscillations and back.

being reflected from edges of the article and being transformed besides, arrive at the radiator in the form of a false echo. Thus when the searching head is positioned as shown in Fig. 213a, beam ИА, being reflected at point A from the left edge of the article downwards in direction AB, reaches the vertex of dihedral angle B, formed by bottom edge and groove, and being reflected from this vertex in the direction of incidence, returns by the same means to the searching head ВАИ in the form of longitudinal UZK. Inasmuch as ИАВАИ is longer than ИКИ, false echo ЛС$_L$ (Fig. 213b), formed by lateral beams will come after the bottom echo and will be seen on the screen to the right of it. However, besides this echo, on the instrument screen still farther to the right will be seen false echo ЛС$_S$, appearing as a result of transformation of oscillations during reflection. So, at point A along with beam AB (longitudinal oscillations) appears beam AC (shear oscillations). Being reflected at point C, beam AC is transformed into two beams – shear oscillations CE and longitudinal oscillations SD. Longitudinal oscillations CD are reflected at point D and reach the searching head within the limits of the solid angle of directivity. ИАСДИ is considerably longer than ИКИ, and moreover, distance AC is traversed by the beam in the form of shear oscillations with correspondingly smaller speed, therefore the false echo will be seen on the screen considerably to the right of the bottom signal. The general form of the image observed on the instrument screen is shown in Fig. 213b,

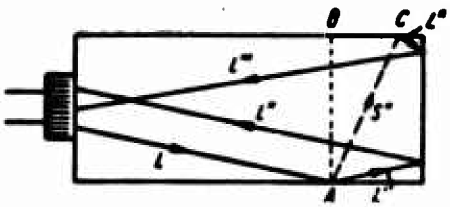


Fig. 214. Conditions of appearance of false echos during control of articles of considerable length.

showing that the amplitude of false echos ЛС$_L$ and ЛС$_S$ is sufficiently great – ЗС – sounding signal.

Analogous conditions of appearance of false echos due to reflections (sometimes multiple) from lateral surfaces can appear also during resounding of articles of great length and comparatively small cross sections: bars, rods, axes, plates, etc. (Fig. 214). As already was noted, echos observed to the right of the bottom signal may not always be ignored. For instance, in the case shown in Fig. 215, the controlled article is a rod in the center the "bottom" surface of which is a shallow recess in the form of a spherical segment. The bottom signal can be obtained only when the searching head is strictly above the center of the recess. However, beams reflected from the lateral surface falling on the surface of the recess can give a false echo visible on the screen with insignificant displacement to the right with respect to the bottom signal: this echo can be obtained also during when the searching head moves relative to the center of the recess.

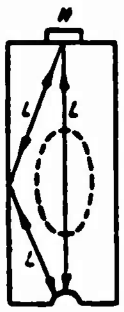


Fig. 215. Distortion of results of control of article as a result of appearance of a false echo.

If in the axial zone of the rod is a coarse granularity, the bottom signal can be absent. However, a false echo will be observed, and inasmuch as the difference of movement of beams forming the bottom signal and the false echo is small, they can easily jumble together. The zone of coarse granularity will not be detected and the judgment about quality of the controlled article will be incorrect.

Considerably more frequently, however, it is possible to make an incorrect decision when false echos are observed more to the left, since they can be taken as echos from defects. In Fig. 216 is given an example of the resounding of an axis having a ring-shaped recess and fillets. Beams proceeding directly from radiator or reflected from the opposite wall can give from these hollows echos ЛС$_S$, arriving earlier than the bottom signal and observed on the screen more to the left of it. If, moreover, on part of the surface of the axis is a thread it also can lead to formation of false echos visible on the screen in the form of a characteristic group of peaks.

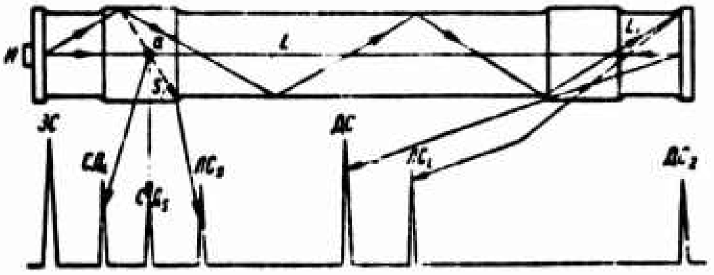


Fig. 216. Spurious signals appearing during control of an axis with ring-shaped recesses and fillets: ДС — bottom echo; ЛС$_L$ — false echo arriving after the bottom signal and formed as a result of reflection of longitudinal oscillations from dihedral angle near the right fillet; СД$_L$ — echo from defect a, formed as a result of reflection of a straight beam; СД$_S$ — second echo from the same defect, formed by shear UZK appearing as a result of transformation of longitudinal oscillations; ЛС$_S$ — false echo formed as a result of reflection of shear UZK.

Longitudinal oscillations reflected from the lateral surface or shear oscillations formed as a result of transformation during reflection can give false echos from edges of face surfaces, arriving after the bottom signal observed to the right of it.

During control of articles of analogous and more complicated form, the time position of the false signals should be fixed (during control of articles of the same type these signals usually are observed in the same points of the scan), and echos from defects must be considered only as such signals whose position on the sweep does not coincide with any one which has been preliminarily fixed. However, a defect can be missed if the echo from it arrives simultaneously with any of the false echos, merging with the last one. In this case a defect can be detected by observing the change of amplitude of one of the false echos due to interference. Preliminary fixation of false echos should therefore include, besides data about time position of echos, also data about their amplitude relative to the bottom echo.

One should especially consider cases of formation of false echos during reflection from flat surfaces (for instance, internal stratifications, the edges of big crystallites, and others) oriented at certain defined angles to the incident ray.

In Fig. 217 is given an example of resounding an article of square cross section, having internal cracks oriented along diagonals of the square (as cracks are usually

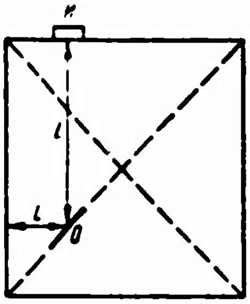


Fig. 217. Distortion of results of control during resounding of a forging of square cross section.

oriented in forgings from high-alloy low-plastic steels; the idealization in our example means that surfaces of cracks are assumed flat). The beam sent by searching head И, falling on the surface of a crack (O) at 45°, after reflection from it reaches the searching head. As it is easy to see, the distance covered by the pulse of UZK (L) is equal to the distance which this pulse would have covered to the bottom edge of the article and back if there were no crack. In other works, on the instrument screen will be seen a false echo from the lateral face of the article on that place where a bottom echo should be observed, i.e., the crack will not be revealed.

It is clear that the surface of a great crack cannot be flat; on it will always be found sections oriented so that the echo from them reaches the searching head, therefore probability that a large crack will not be revealed is very small. However, small (but sometimes impermissible) cracks may be missed. Probability of missing cracks increases also with decrease of frequency of UZK, inasmuch as ratio of wave length to average height of unevenness of reflecting surface is increased and character of reflection from a diffuse character becomes all the more mirror like. Obviously, to increase reliability of control, resounding of important blanks in which similar internal cracks can appear, oriented along diagonals of the square should be conducted not only with longitudinal UZK introduced along the normal to the surface of the blank, but also by means of introduction of shear UZK at 45° to this surface.

In Fig. 218 is given an example of resounding a body in the form of a parallelepiped or a cylinder of height A and diameter B. When an internal disturbance of continuity O exists, oriented at 45°, on the instrument screen will be seen a false echo which, according to depth meter readings can be accepted as a signal from defect O' oriented in parallel to the surface of introduction of UZK and located at depth $H = h + b$.

If $h < A - b$, the false echo will be observed on the screen more to the left; if $h > A - b$, then more to the right; finally, when $h = A - b$ — the false echo will be merge with the bottom signal. This naturally can lead to serious misunderstandings: the controller can pass the blank for further treatment, thinking that at depth H according to the drawing is a hole during the boring of which the

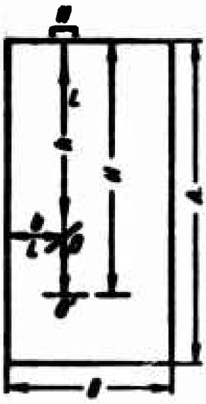


Fig. 218. Distortion of results of control upon detection of a crack oriented at 45^o. Coordinates of crack are determined incorrectly. If height of article $A = h + b$, the crack is not revealed.

defective zone will be removed. In reality, defect O, lying at depth h will remain in the blank after treatment and can subsequently essentially lower the strength of the article.

In order to increase reliability of control of important blanks in which the presence of internal defects oriented in the same manner is possible, first of all (if this is possible) a repeat resounding from the opposite surface must be made. If the defect is oriented in parallel to the planes of introduction of UZK, the sum of readings of the depth meter, obtained during resounding from both sides will equal the height of the blank. If, however, the defect is oriented at an angle of 45^o, during resounding from the opposite surface the eading of the depth meter will correspond to the depth of bedding of the defect plus its distance from the right edge of the blank, and the sum of the height of the blank and its transverse dimension. On the basis of these measurements, a conclusion can be made concerning presence of a defect oriented at 45^o, and exactly indicate its coordinate.

Reliability of control may also be increased if, as in the preceding example, additional resounding by shear oscillations is made, introducing a beam at an angle of 45^o to the surface.

False echos, similar to those considered in the last example can be observed also if the defect is oriented at an angle ~60-65° (for the majority of metals) to the incident beam. Such a case is shown in Fig. 219. Beam L, incident on the surface of defect O (longitudinal UZK), is transformed upon reflection into two beams — longitudinal oscillations L', reflected in the direction of the bottom edge, and shear S', reflected along the normal to the lateral surface of the blank. reflected from this surface, shear oscillations fall on th surface of the defect and are transformed a second time upon reflection: there appear beams S'' — shear oscillations, reflected in the direction of lateral face, and L'' — longitudinal oscillations, taken by searching head in the form of false echo. Depth meter readings will correspond to detection of imaginary defect O', located at depth $H = h + \frac{c_L}{c_S} b$. A false echo will be observed on screen more to the left if $h < A - \frac{c_L}{c_S} b$, to the right if $h > A - \frac{c_L}{c_S} b$, and will merge with the bottom signal

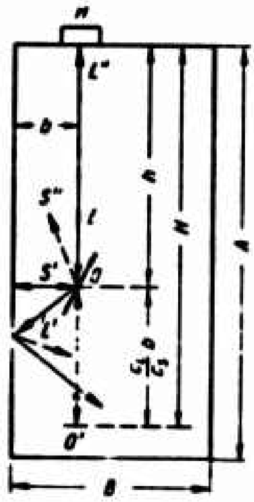


Fig. 219. Distortion analogous to that shown in Fig. 218, connected with transformation of UZK upon reflection from a crack oriented at an angle of 60-65° to the surface on which the searcher is located.

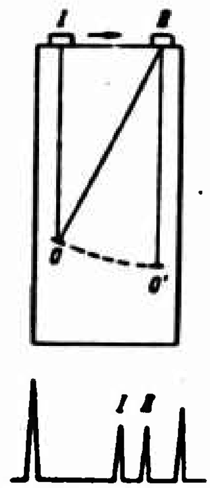


Fig. 220. Distortion of instrument readings as a result of diffuseness of reflection of UZK from rough surface of defect.

$h = A - \frac{c_L}{c_S} b$. Just as in preceding cases, reliability of control can be increased by means of bilateral resounding and resounding by shear oscillations introduced at a corresponding angle.

In the given examples we assumed the reflector to be flat. However, as is easy to show, during reflection from a real defect with a rough surface the picture does not change in principle but in a number of cases is complicated.

Let us assume that in a body of elongated form is an internal crack oriented as is shown in Fig. 220. When the searching head is placed above the crack in position I, an echo from the defect will appear due to diffuseness of reflection of the vertically incident central beam. However, amplitude of the echo will be small, inasmuch as angle of incidence of beam on surface of defect is sufficiently great. As the searching head advances in the direction shown by the arrow, UZK emerging from the radiator at ever greater angles to the axis of its field will fall onto the surface of the defect. Intensity of UZK will somewhat drop, but simultaneously reflectivity of longitudinal UZK in the direction to the searcher will be increased,

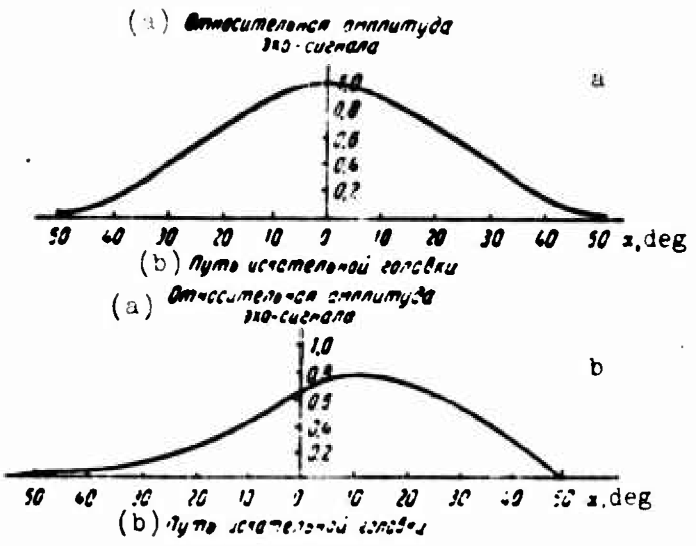


Fig. 221. Determination of orientation and location of defect according to form of a rounding "roaming" echo. Defect is oriented in the plane parallel to the surface of introduction of UZK – a, and in the plane slanted to the right – b; α – angle between axis of radiator and direction to defect.
KEY: (a) relative amplitude of echo; (b) path of searching head.

and as a result amplitude of the echo, which at first remained approximately constant, when the head reaches position II at which the lateral beam will be oriented perpendicular to the crack, will somewhat increase. Due to this, the operator may assume that the defect is not at point O, where it indeed is, but at point O', lying on the axis of the field of the searching head fixed in position II.

If the reflecting surface of the defect is sufficiently great, then according to the form of the rounding echos observed on the screen as the searching head advances in the direction of the arrow it is possible in a number of cases to judge orientation of defect and its location. Thus, if a defect is oriented in the plane parallel to the surface of introduction of UZK the amplitude of the echo smoothly changes and the rounding is symmetrical, having the form of a bell (Fig. 211a). If, however, the defect is oriented obliquely, then as the searching head approaches a defect from the side in which the normal to its surface is turned, the amplitude of the echo at first smoothly increases and then (considerably faster) drops to zero; the rounding besides is asymmetrical with a shifted maximum (Fig. 221b).

False echos can appear also during control by a refracted beam, according to Fig. 222. Shear UZK (beam S) are introduced into the controlled article at an angle β, and, encountering reflecting plane O, oriented at an angle β/2 with respect

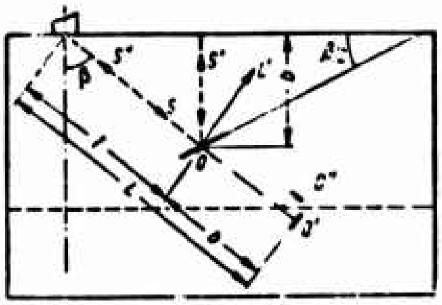


Fig. 222. Distortion of instrument readings during control by shear UZK.

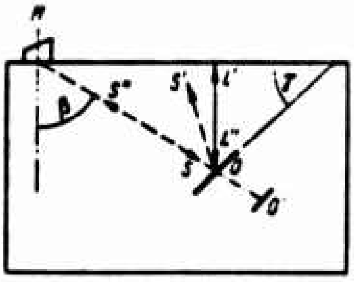


Fig. 223. Example analogous to that shown in Fig. 222. Distortion of readings occurs as a result of transformation of shear UZK into longitudinal.

to the surface of the introduction of UZK are reflected from it perpendicularly to the surface of introduction of UZK (beam S'), after which they return to point of introduction (beam S'') by the same means. A false echo from defect located from point of introduction of UZK at a distance $L + l + b$, will be registered, i.e., coordinates of defect will be determined incorrectly. Depending upon thickness of an article either coordinates of point O', located on the line of the introduced beam at a distance b after the reflecting plane, or of point O'', located at the same distance on the line of the beam reflected from the lower edge of the article (designated by the dotted line in Fig. 221) can be shown. False echo will appear also if shear oscillations introduced in articles at an angle β encounter a flat reflector oriented at an angle $\gamma = \frac{c_L}{c_S} \arcsin \frac{\beta}{2}$ (Fig. 223). In this case a spurious signal appears as a result of reflection of longitudinal oscillations from surface of introduction of UZK, formed as a result of transformation from shear when they are incident on the surface of the reflector. Coordinates of defect will be determined also incorrectly (Fig. 223).

In the two last examples it was assumed that reflector was flat and reflection was mirror reflection. Under this condition detection of defects and correct determination of their location is possible only if the defect with respect to the incident ray is oriented at an angle close to 180°. Real defects, as is known, are revealed when orientation is at under angles other than 180°. From this, however, it does not follow that the considered examples have no practical value. Thus, if in an article resounded by an oblique beam is a hole of sufficiently large diameter, a false echo will be obtained. Reflection from cylindrical surfaces of

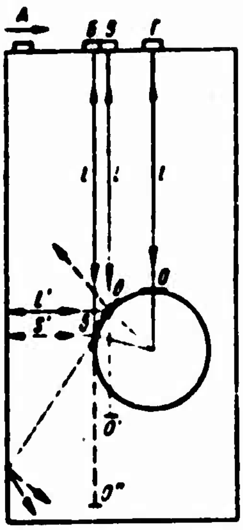


Fig. 224. Distortion of instrument readings as a result of reflection of UZK toward the lateral surface and occurring transformation of UZK. Instead of a cylindrical cavity of considerable diameter, the instrument shows five small defects of which four are false.

such a hole presents special interest, and therefore it should be considered separately.

Let us assume that the controlled article is a right angle parallelepiped with a round hole whose axis lies in the plane parallel to the plane of introduction of UZK (Fig. 224). If we shift the searching head in the direction of the arrow, in zone A on the instrument screen will be observed a bottom signal; then at point Б it will disappear and a false echo will appear, corresponding in depth meter readings to a defect located at point O". This false echo appears as a result of reflection of the beam from a cylindrical surface at point б at which the beam is incident on the plane tangent to this surface at an angle near 62°. In accordance with the example considered above, in the direction of the lateral face are reflected shear oscillations. With further advance of searching head echos are not observed before point B. At this point a false echo appears, corresponding to the defect located at point O' and formed as a result of the incidence of the beam at point b on the plane tangent to the cylindrical surface at an angle of 45°. There are no further echos before point Г, where there is direct reflection from cylindrical surface at point O, where the plane tangent to this surface is parallel to surface of introduction of UZK. With further advance of searching head in the direction shown by the arrow, the described picture is repeated in reverse order.

Reflection of UZK from a cylindrical or spherical surface leads to appearance of false echos during control of articles in the form of bodies of revolution (rods, shafts, spheres, axes) when oscillations are introduced by a searching head with a flat radiating surface. The acoustic contact in this case is a point contact or a linear contact, which leads to considerable increase of the angle of divergence of UZK. As can be seen from Fig. 225, beams departing at an angle $\alpha = 30^{\circ}$ to the field axis experience double reflection and are taken by the searching head. The interval of time from sending of pulse to reception of reflection by searching head corresponds to the perimeter of an equilateral triangle inscribed in a circle. On the instrument screen will be seen a false echo $ЛС_L$, shifted to the right relative

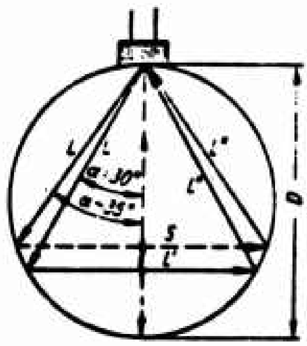


Fig. 225. Distortion of instrument readings during control of rod material (stratification oriented along vertical diameter can be not revealed).

to the bottom echo by magnitude corresponding to (for steel):

$$\frac{3}{2} D \cos \alpha - D = 0{,}3D,$$

where D — diameter of article.

Beams departing at an angle $\alpha = 35^{\circ}$ also may cause the appearance of a false echo as a result of transformation of longitudinal oscillations into shear at the first reflection and shear into longitudinal at the second. Simple calculations show that this echo $ЛС_S$ will shift to the right of the bottom signal by a magnitude corresponding to 0.67 D.

Inasmuch as spurious signals formed by longitudinal and shear oscillations will be taken by the searching head independently of one another, the picture observed on the screen of the instrument will take the form shown in Fig. 226.

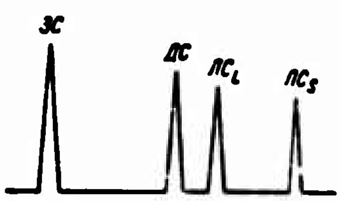


Fig. 226. Echos observed on the instrument screen during resounding of a cylinder according to Fig. 225.

If there is a defect in the article (for instance, a crack stratification) oriented along the vertical diameter, as was shown in Fig. 224, then, not being revealed by UZK introduced in the direction of the same vertical diameter, it would seem that it could be revealed by longitudinal and (independently) shear UZK incident perpendicularly to its surface. However, as is not difficult to see from Fig. 224, echos from longitudinal, and correspondingly from shear oscillations, in the considered case will merge on the screen with false echos $ЛС_L$ and $ЛС_S$ (Fig. 226), not allowing a conclusion about the existence of a defect.

Similar doubled echos from a defect, formed by longitudinal and shear UZK can be observed (and even more to the left of the first bottom reflection) in articles of considerable length when the cross section is comparatively small. Thus, if in the article depicted on Fig. 216 is a defect located at point a, from it will be reflected longitudinal UZK, propagating along the axis and, shear UZK, formed as a result of transformation upon reflection from the lateral surface. On the screen more to the left of the right bottom reflection will be seen two echos from the defect $СД_L$ and $СД_S$. It is not difficult to recognize that the echos can be observed in the presence of defects in articles given in the remaining examples.

Fig. 227. Appearance of a false echo as a result of reflection of a surface wave from the edge of an article.

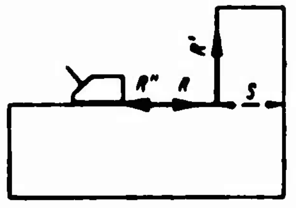


Fig. 228. Appearance of a false echo during control by surface waves as a result of partial transformation of surface waves into shear.

In certain cases the appearance of spurious signals can be observed during control of articles of simple form by longitudinal UZK. In this case they are caused by the appearance of surface waves due to partial transformation of longitudinal waves. Propagating along the surface of the controlled article, and being reflected from its edge, surface waves can cause an echo visible on the screen (Fig. 227).

Possible also is the appearance of shear UZK by partial transformation of surface waves. Such an example is shown in Fig. 228. During control of an article by surface UZK (R), a "step," the waves partially turn along the surface (on the figure — beam R'), are partially reflected from point of turn to the searching head (beam R''), partially (due to the shear component) propagate in the direction shown by the dotted line (beam S), and give a reflection from the opposite (on the figure — the right) surface of the article.

We considered a series of examples of distortion of echo-flaw detector readings as a result of the appearance of different false echos on its screen.

In composing methodalogy of control, it is necessary to consider also the possibility of distortion of readings connected with interference phenomena affecting sensitivity of the instrument.

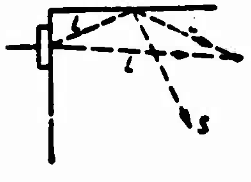


Fig. 229. Distortion of instrument readings as a result of interference of a straight beam with a beam reflected from the lateral surface of an article.

In Fig. 229 is given the diagram of detection of a defect located near the lateral surface of an article [94]. During propagation of longitudinal UZK radiated by searching head two beams can simultaneously reach the defect: a direct beam proceeding from the searching head, and one reflected from the wall of the article. Surface of the defect is not ideally smooth, therefore the beam from the lateral wall can partially be reflected in the direction of the searching head just as the direct beam. The distances travelled by the direct beam and the beam reflected from the lateral surface are different, therefore with sufficient pulse duration amplification or weakening of the total echo can be observed due to interference of oscillations. Effect of interference is

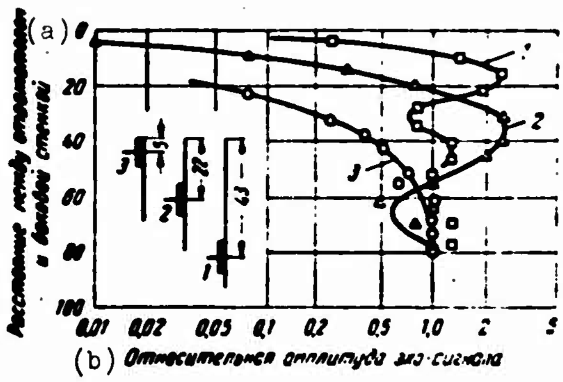


Fig. 230. Change of amplitude of echo signal from a defect located short distances from the lateral wall of the controlled article.
KEY: (a) distance between reflector and lateral wall; (b) relative amplitude of echo signal.

determined by difference of movement of beams and depends on distance of defect to lateral wall and also on position of searching head, which is illustrated in Fig. 230. From curves on Fig. 230 one may see that sensitivity sharply drops with decrease of distance from defect and from searching head to lateral wall. When distances between head and lateral wall are small, sensitivity fluctuates when distance from defect to lateral wall changes (Fig. 230).

It follows from this that a small defect located directly near the lateral wall can not be detected by a normal head placed near the edge of the article. It is more reliable in this case to use surface or shear waves, directing them as is shown in Fig. 231.

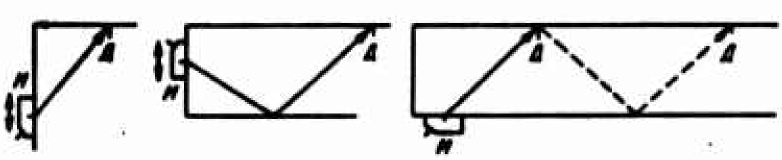


Fig. 231. Detection of defects located near lateral surface using refracted shear UZK: И – searching head; Д – defect.

The considered examples obviously do not exhaust all possible cases of appearance of false echo signals, distorting flaw detector readings. However, even this is sufficient to affirm that in formulating methodology of the control of important articles, one should thoroughly analyze the possibility of appearance on the echo-flaw detector screen of different echos visible more to the left and to the right of the first bottom reflection and interpret these echos in reference to

the given section of the controlled article. Facilitation of interpretation of visible echo signals, and consequently increase of reliability of control, can in a number of cases be attained by means of consecutive or simultaneous resounding in different directions with introduction of UZK along the normal to the surface of article, and at various angles different from normal. Adjustment of sweep length, making it possible to remove from the screen all signals visible to the right of the first bottom reflection, is inadvisable in this case.

This can be done by using several independent flaw detectors, but obviously it is more advisable to create a special flaw detector, having several searching heads and allowing observation of signals from each of them independently. The immersion variant of the echo method possesses absolute advantages for realization of combined resounding with introduction of UZK at different angles to the surface.

e. An Instrument of the Acoustic Contact Type. Ways to Improve Characteristics of Searching Heads. Selection of a Scanning Program.

In selecting the type of acoustic contact it is necessary to consider necessary efficiency of control, overall dimensions and complexity of form of article, volume of production of this article, and other factors.

The greatest efficiency with corresponding mechanization and automation of control is naturally in immersion contact. However, automated control of articles of complicated form requires creation of special programming devices to change the angle of introduction of UZK in different points of surface of the article. Creation of such complicated and expensive devices can be profitable only in mass production. If, however, an article is produced in small quantities, that expenditures on construction of an installation for control by the echo method in the immersion variant are justified only if form of article is sufficiently simple. It is necessary to note that the cost of the immersion installation includes also system for supply, filtration, and degassing of water. In the control of large-scale articles the volume of the bath is large and the quantity of water which must periodically be purified and degassed is measured by the tens of tons. Degassing of water is necessary to decrease level of noises created by air bubbles. Periodic purification is needed, inasmuch as during control water is inevitably contaminated mainly due to residues of lubricant on the surface of the article. To prevent contamination of water, and mainly to increase stability of acoustic contact, the surface of the controlled article before submersion in the bath must be thoroughly

degreased. A small quantity (tenths of one percent) emulsifier (for instance [OP-7] (ОП-7)) should be added to the water, increasing moistening ability of the water. Stability of acoustic contact, understood as constancy of the transmission coefficient (and reflectivity), plays a decisive role in methods requiring quantitative appraisal of results, including the method of acoustic compensation of oscillations.

To guarantee stability of jet contact, besides conditions stipulated for the immersion method constancy of water feed pressure is required. Therefore supply of water under static (for instance pneumatic) pressure has an advantage over supply by pump.

In contact conditions through a film of lubricant stability is more difficult to ensure since this requires a strictly constant pressure pressing the head to the surface of introduction of UZK and causing the presence of a layer of liquid between this surface and the contact surface of the head. When longitudinal UZK are introduced along the normal, stability of contact is frequently judged according to constancy of amplitude of the bottom echo. However, such an appraisal is not reliable, since it does not consider changes of amplitude of the bottom echo due to strong scattering of UZK in zones of coarse granularity and also due to oscillations of reflectivity of UZK on bottom surface of article (in immersion variant).

The only correct criterion for appraisal of quality of acoustic contact is measurement of coefficients of transparency and reflectivity of UZK from surface of introduction of UZK.

This problem when a refracting head is used can be solved by means of measurement of the amplitude of UZK reflected from the contact surface of the searching head. A special design of such a head has been proposed by Lutsch.[1] In this head a special piezoelectric element glued to the front edge is used for measurement.

Van Valkenburg[2] has proposed to control quality of acoustic contact when working with a refracting head by using a special piezoelectric element located on the upper edge of the head and sending pulses of longitudinal UZK along the normal to the surface of the controlled article. By number and amplitude of obtained

[1]A. Lutsch DBP, 1013898, 1954.

[2]H. van Valkenburg. American patent 2651012, 1952.

bottom echos it is possible (with a special indicator) to judge quality of contact.

A more original solution to this problem for direct contact has been given by Yu. N. Shtremer [238]. His method provides determination of amplitude and phase of longitudinal oscillations reflected from the contact surface of the searching head and reaching a special piezoconverter mounted on the front edge of this head. Change of quality of contact leads to certain change of amplitude of reflected UZK and very sharply affects magnitude of phase angle, inasmuch as when contact of body of head with controlled article is tight, reflection occurs without loss and when there is an air gap — with a half-wave loss.

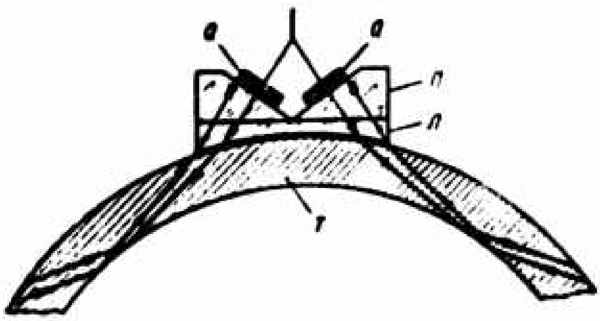
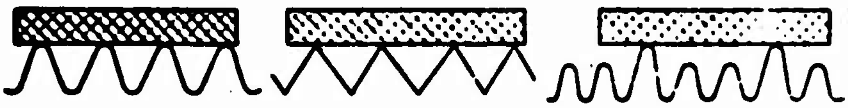


Fig. 232. Quality control of acoustic contact in the operation of a refracting searching head. Two heads connected in parallel [142] are used: Q — piezoconverters; П — prism; Л — lens; T — controlled article.

The enumerated methods require complicating the design of the searching head and introducing additional elements in the setup of the actual instrument. This is possible to avoid if two ordinary refracting searching heads connected in parallel and oriented "face to face" are used [142]. On the instrument screen (when acoustic contact is normal) a sounding pulse, two echos from each defect (Fig. 232), and also the pulse which passed through the article are observed.

In conditions of introducing longitudinal UZK along the normal to the surface of the article in the contact variant, a simple and reliable method of quality control of the acoustic contact in industrial conditions is still lacking.

Kloth [239] experimentally studied quality of acoustic contact in the contact variant for the range of frequencies 0.5-5 MHz. He compared amplitudes of echos observed on the screen of a tube with the help of an attenuator making it possible to obtain a weakening of 99 dB in steps from 1 dB with an error of not more than 1%. Kloth established that as a contact lubricant best results are from machine oil.



a b c

Fig. 233. Influence of quality of surface treatment of controlled article on quality of acoustic contact.

In using such a lubricant the multiple breaks and contacts of the searching head to the ground surface of metal gives a scattering of amplitude of the echo within limits of 12%. When the head slides forward this scattering does not exceed 3%.

Impairment of thoroughness of treatment of the surface of the article causes an increased gap, and consequently lowers transmissivity of the system. Besides wear of contact surface of searching head is increased, inasmuch as different solid particles can more easily be held balk in depressions of the relief.

The basic requirement in the preparation of the surface of the article for uniform thoroughness of treatment of the whole surface of introduction of UZK. From this point of view treatment somewhat less thorough but consistent over the whole surface of the article is more profitable than greater thoroughness of treatment, if on separate sections (even a small area) the surface will be rough.

What was said is explained by Fig. 233, showing that with a more rough but evenly treated surface (Fig. 233a) contact is over a larger area than when the surface is thoroughly treated but is considerably uneven. In the last case (Fig. 233c) the contact surface of the searching head descends only on projecting points of the relief and the contact area decreases. Therefore, before control all particles and contamination must be removed and sections with scale (especially flaking), traces of corrosion, of paint, etc. are thoroughly cleaned with a scraper, steel brushes, a felt disk or rags. Cleaning with abrasive wheels can be used only very carefully, inasmuch as it can lead to formation of deepenings on the surface of the article.

The contact area can be different even when height of unevennesses on the surface are identical, as Fig. 233b shows: height of the uneven areas is the same as in Fig. 233a but the tips are sharper. Naturally the contact area in this case will be less and the transmission coefficient of UZK – lower. Obviously quality of contact worsens still more because the liquid contact film can be torn by sharp projections.

Everything indicates that correct selection of degree of thoroughness of surface treatment is problem in which different factors must be considered. The necessary degree of thoroughness of treatment can be determinedwith sufficient accuracy by Fig. 86 despite the fact that these curves are obtained for ideally smooth surfaces. Practice shows that degree of thoroughness of surface treatment determined by these curves is only insignificantly oversized, which is easily explained by the above considerations.

A uniform oxidized film or a paint and varnish coating practically do not hinder control, only somewhat lowering sensitivity. The majority of intermediate products made by a rolling, a pressing, a drawing from scale-resistant metals, and alloys can therefore be subjected to control without special preparation of surface. The same pertains to flat sections of certain stamped articles. Forged articles, if forging was carried out by a striker with a polished surface or using a lining in the form of a polished plate and if on the surface of articles there remained no graduated relief, also in a number of cases can be checked without special preparation of the surface. If, however, the surface of the forging is not smooth, machining (sharpening, milling) is necessary to create a smooth surface.

The surface of steel articles in a number of cases can be well prepared by sandblast treatment or sandblast cleaning by steel shavings.

Chemical etching for this purpose can be used only when it is assured that etching will have no harmful influence on the metal.

A criterion of surface smoothness can be the ratio of average height of unevenness of surface R_z to length of elastic wave in the contact liquid. Practice and calculation (Fig. 86) show that for control by the contact echo method requirements for the surface are very high, since the transmission coefficient maintains a value close to maximum only when the degree of surface treatment ($R_z < 0.01 \lambda$) is greatest. When treatment is less thorough, the transmission coefficient sharply drops.

During immersion contact the surface, as in optics, may be considered smooth when $R_z < 0.005 \lambda$. If height of unevenness is greater, diffuse scattering of UZK is observed which becomes especially noticeable at $R_z \geq 0.5 \lambda$, when tracks of treatment by cutter start to play the role of a diffraction grating, which to an even greater degree promotes decrease of energy of UZK introduced into the article along the normal to its surface. The observed fall of sensitivity can be partially

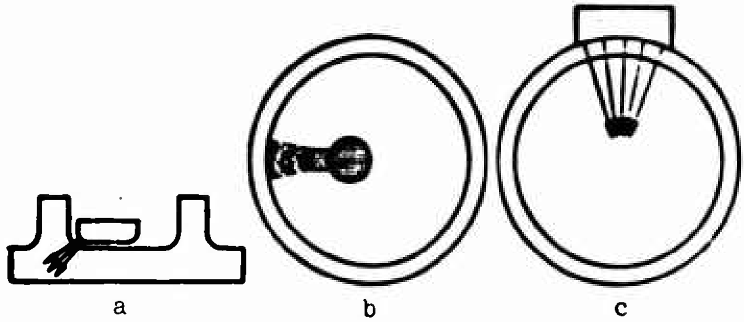


Fig. 234. Coordination of form of radiating surface of searching head with form of surface of controlled article: a,c – in contact variant; b – in immersion variant.

compensated by increasing the power of the radiated pulse of UZK.

Curvature of surface of article causes additional complications connected with reduction in contact area when heads with a flat contact surface are used. According to Krautkrämer [94] the angle of divergence of UZK at a frequency of 2 MHz introduced into a cylinder 500 mm in diameter of steel or aluminum alloy practically does not differ from angle of divergence in an article with a flat surface. However, if diameter of cylinder is decreased to 100 mm, angle of divergence is increased one and a half times. Amplitude of the echo from defects in these conditions decreases 3-5 times. In connection with this, during control by the contact echo method it is necessary to coordinate form of contact surface of head with form of surface of article: it is possible to use piezoelectric converters made of plates which are bent, or mosaic, composed of separate flat plates mounted so that the radiating surface has the needed curvature, or finally, flat, glued to special adapters executing the role of a lens (Fig. 234). When UZK are introduced along the normal to the surface, use of adapters is possible only when the limiting conditions ensuring absence of interferences from flutter echoes in body of adapter are observed. As a rule introduction of UZK through a convex surface is easier than through a concave surface.

In the control of cylindrical articles by shear UZK the contact surface of the searching head can be exactly fit to the surface of the article. However when curvature of this surface is significant lateral rays of the divergent beam of UZK can be directed at angles of incidence which cause the appearance of surface waves (Fig. 235), which may cause the appearance of spurious signals on the flaw detector screen.

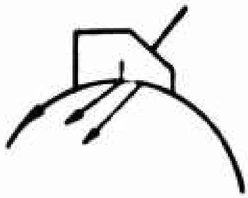


Fig. 235. Possibility of appearance of false echos as a result of formation of surface waves during control by a refracting searching head fit to a cylindrical surface.

Analogous phenomena can be observed in the immersion contact variant. In this case considerable refraction of UZK can lead to formation of interfering signals from shear oscillations excited on the surface of an article of cylindrical or spherical form.

Therefore creation of all-purpose heads and heads giving a parallel beam of UZK is a very important problem.

For mass control of articles of the same type it is advisable to make special searching heads in the form of the contact surface, ensuring best conditions of control, as is done, for instance, in the specialized echo-flaw detector UZDL-61, designed to detect cracks on edges of blades of gas turbines.

The cheapest and most accessible contact liquid for any method of acoustic contact is first of all water.

Water is successfully used in the contact variant of the echo method, for instance, in the control of rails and also during control of different articles in immersion and jet variants. The use of water as a contact liquid is limited by the possibility of corrosive damage of controlled articles, insufficient moistening ability, and small viscosity. This forces the use of anticorrosive additives (inhibitors) and additions of superficially active materials to increase moistening ability. Small viscosity of water does not permit, however, introducing UZK through vertically oriented edges of the article.

In connection with this, for the contact variant of the echo method, the contact liquid is usually machine or transformer oil, black oil, a mixture of lubricating oil with gasoline, glycerine, and others. As a rule, for a lubricant for smooth surfaces less viscous and for rough surfaces — more viscous oils are used.

For contact with a vertical surface different pastes can be applied, for instance, a mixture of methylcellulose and glycerine with water.

Krautkrämer indicates the advisability of using as contact liquid a concentrated solution of sugar, noting as a special advantage that the surface of the article, the head and also the hand of the operator after control can easily be washed with water.

During control of articles from materials not possessing high electrical conductivity (for instance, an article from plastic) and when using a searching head with unprotected and nonmetallized radiating surface of piezoelement to the contact liquid or paste it is possible to add a metallic powder (lead tungsten). Firestone [240] and Lutsch [241] recommend the use of metallic (copper, tin) foil around 20 μm thick to increase the transmission coefficient UZK from quartz through a butyric layer into metal, explaining this effect by the increase of impedance of the contact layer.

Recommendations in literature for the control of metallic articles at high temperatures using as contact liquids cylinder or silicon oil (temperature of oxidation near 300°C) should be used very carefully, inasmuch as even at a lower temperature the searching head can break down.

Use of thin foils permits also an improvement of one of the most important exploitational characteristics of a searching head — its resistance to wear.

Above methods to increase resistance to wear of searching heads already were considered, providing protection of the piezoelement by caps of thin plastic or metallic foil. Detachable caps from plastic are used in heads of echo-flaw detectors of Siemens and Krautkrämer [FRG] (ΦΡΓ), protective caps from stainless steel 0.15 mm thick are glued to the piezoelement of heads of type [I-10] (И-10) of the domestic echo-flaw detector V4-7I.

Header of cap protects piezoelement from wear and constitutes an intermediate shell whose acoustic properties can essentially affect effectiveness of work of head.

Therefore the choice of material for the protective must be made taking into account its mechanical and acoustic characteristics.

Obviously this material should possess a low specific gravity to minimize the general mass of a complicated vibrator, high mechanical properties — hardness and resistance to abrasion to increase resistance to wear, low attenuation factor of UZK to lower energy losses, large value of rate of propagation of UZK to decrease of wave thickness of header.

It is obvious also that magnitude of specific wave resistance should satisfy the condition of coordination of material of piezoelement and controlled article. Speaking as conditionally as possible about compatibility and enlightenment in reference to considered conditions we should note that compatibility and enlightenment, as experience shows, appear in sufficient measure.

If we originate from idealized conditions (infinitely extended medium, absence of glue and butyric layers, continuous radiation), it is possible to consider that for full agreement of the value of specific wave impedance of material of the protective cap W_{3K} should be equal to the mean geometric value of specific wave impedances of material of piezoelement W_{Π} and load (controlled article) – W_H:

$$W_{3K} = \sqrt{W_H W_{\Pi}}.$$

For a quartz piezoelement of radiating into steel or into aluminum, the value of W_{3K} is $26.4 \cdot 10^6$ and $16.1 \cdot 10^6$ kg/s·m² correspondingly. Replacing quartz by lead zirconate titanate, for radiation into steel we will obtain $40 \cdot 10^6$ and correspondingly for radiation into aluminum – $24.2 \cdot 10^6$ kg/s·m².

In Table 8 are given mechanical and acoustic characteristics of certain materials recommended by different researchers for use as protective caps of headers and compatible linings.

Table 8. Physicomechanical Characteristics of Materials Utilized for Protective Caps and Headers

Material	ρ, 10^{-3} kg/m³	Brinell hardness	Resistance to abrasion	Rate of propagation of longitudinal UZK c_{np}, m/s	Damping	Specific wave impedance W_{3K}, 10^6 kg/s·m²	Deviation of W_{3K} from $\sqrt{W_{\Pi} W_H}$, % for materials: quartz-steel	quartz-aluminum	ЦТС-steel	ЦТС-aluminum
Teflon	2,2	—	Average	1350	High	3,0	−88	−81	−93	−88
Porolon	1,2	—	»	1900	»	2,3	−92	−87	−94	−90
Copper	8,9	40	Low	4700	»	41,8	+16	+26,5	+4	−72
Bismuth	9,8	9	»	2180	»	21,4	−16,5	+36	−46	−12
Cadmium	8,6	22	»	2780	»	24,0	−6,5	+53	−40	−1
Tin	7,3	5	»	3320	»	24,2	−5,8	+54	−40	±0
Lead	11,3	4	»	2160	»	24,5	−4	+57	−38	+1
Steel	7,8	100	High	5850	Average	45,6	+80	+190	+14	+88
Quartz	2,65	—	»	5760	Low	15,2	−45	−11	−62	−37
Beryllium	1,85	100	»	12000	»	22,6	−15	+44	−43	−6

Analysis of these characteristics shows that plastics cannot be compatible media, since their specific wave impedance differs from required values by 80-95%. Wave thickness of headers from plastics is considerable; therefore a quarter wave layer on megacycle frequencies virtually cannot be realized. The low strength leads to the fact that the header can be not less than 0.5-0.8 mm thick, and this means that such headers can be used only on low frequencies (~0.5 MHz). With increase of frequency, damping of UZK sharply increases, and a flutter echo is observed as a

result of which sensitivity and resolving power drop.

Obviously application of protective caps is justified only during control on low frequencies of articles with a roughly treated surface, since plastic becomes imbedded in deepenings of surface relief which improves contact.

Soft metals indeed can play the role of a compatible media for specific combinations of materials of piezoelement and controlled article. Thin foils from these metals can be used as a translucent layer. An obstacle in application of such foils is mainly their low mechanical properties.

Steel can be satisfactorily compatible only for a lead zirconate titanate-steel system. In the remaining cases considered in Table 8 it cannot be a compatible medium inasmuch as its specific wave impedance very considerably differs from required values. Therefore reflection of UZK from internal and external surface of header is inevitable. In order that multiple reflections of UZK inside the header do not prolong the sounding pulse, the header must have minimum thickness (0.1-0.15 mm), which naturally lowers resistance of head to wear.

Quartz as a header can give a satisfactory compatibility during control of aluminum articles, and its use sometimes can be justified by the low specific gravity, high hardness and resistance to abrasion. Fragility of quartz limits possibility of its use.

The best combination of necessary properties belongs to beryllium, proposed by the author as material for protective headers. Beryllium gives a very good compatibility for quartz-steel and lead zirconate titanate-aluminum systems, possesses an insignificant wave thickness (for a frequency of 2.5 MHz thickness of quarter-wave plate is 1.2 mm), different mechanical properties and low damping of UZK.

An experimental check completely confirms what has been said. Prolonged tests in industrial conditions of heads developed by the author and N. V. Babkin[1] with beryllium protection showed that in all parameters these heads exceed all others, possess excellent sensitivity, resolving power and very high resistance to wear.

Beryllium protection has been developed as suitable for normal searching heads. For refracting heads the problem of wear can be solved by application of steel or aluminum prisms for heads radiating shear waves and brass prisms for heads radiating surface waves.

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[1]D. S. Shrayber, N. V. Babkin. Author's certificate No. 120948, USSR, 1957.

In the control of articles of simple form containing defects of different orientation, combined searching heads containing several piezoelements differently oriented can be used. When these elements are connected in parallel they simultaneously send longitudinal UZK along the normal to the surface of the article and shear at different angles of refraction (sending surface UZK is possible also). Such heads were applied by Martin and Werner [211] for the control of railway rails, railroad car axes, etc., and made it possible to obtain a more distinct idea about location of revealed defects, their character and orientation.

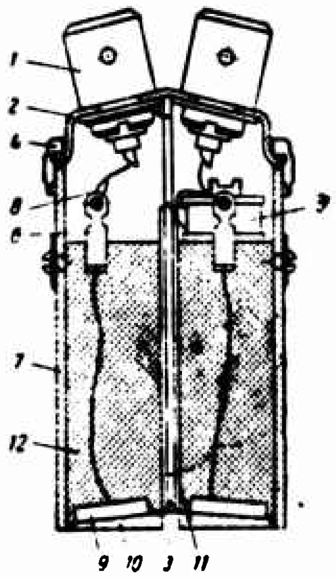

Fig. 236. Separately combined searching head SKB UZD (diagram): 1 – joint; 2 – cover 3 – screen; 4 – nut; 5 – coil; 6 – platelet; 7 – body; 8 – lead out; 9 – piezoelectric element; 10 – prism; 11 – wall; 12 – damper.

Heads of combined type, containing two piezoelements can be used in different cases. Above application of such heads for control of acoustic contact when UZK are introduced not along the normal to the surface of the article was indicated. It was also possible to use separate combined heads with two piezoelements for the purpose of obtaining a small dead zone to increase sensitivity to defects lying at a great depth, etc.

For instance, in the separate combined searching head shown in Fig. with plastic prisms, developed by the [SKB UZD] (СКБ УЗД) in 1961, strong refraction of UZK during passage from plastic into metal is used which permits obtaining a dead zone of around 0.5-1 mm. However, as can be seen from the diagram of movement of beams, sensitivity of such a head drops rapidly with an increase of depth of bedding of defect. In order to make this sensitivity more uniform in the separate combined searching heads[1] developed by the author in 1951 two piezoelements are used as a radiator and two as a receiver of UZK. Piezoelements are placed so that one of them sends a beam at a considerable angle to the normal, ensuring detection of defects lying at a shallow depth under the surface; the other sends a beam along the normal, ensuring that a bottom signal is obtained and deep defects are obtained (Fig. 237a). An analogous result can be obtained also if in the radiating and receiving heads, containing piezoelement each, the field is split.

[1]D. S. Shrayber. Author's certificate No. 100284, USSR, 1951.

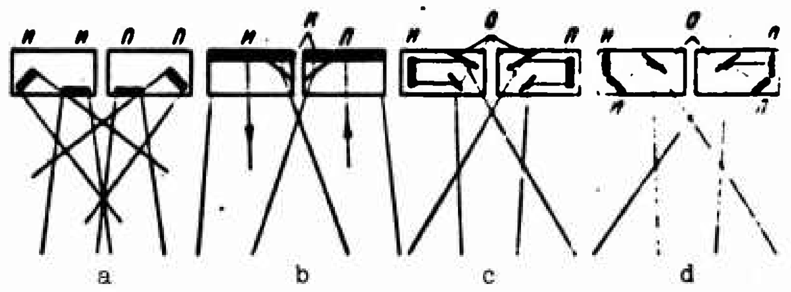

Fig. 237. Separate combined searching heads making it possible to obtain more uniform sensitivity in considerable limits with respect to depth of bedding of defect: И – radiating; П – receiving piezoelements; K – refracting wedges; O – reflecting edges.

A head with a split field can be created, for instance, by using a wedge inserted in the header of the searching head and made of a material in which rate of propagation of UZK sharply differs from rate of their distribution in material of header (Fig. 237b). Such a head was made by M. E. Khurgin [243]: a brass wedge was inserted into a steel header, which made it possible to balance sensitivity with respect to depth. Such a wedge can be used very effectively in combination with a beryllium header.

Splitting of a field can also be realized without a wedge if on the path of UZK in the body of the head at corresponding angles reflecting edges are placed, directing part of the UZK at the needed angle (Fig. 237c).

A separate combined head in which is combined application of a pair of differently oriented piezoelements, reflecting edges and materials sharply distinguished in rates of propagation of UZK is more compact. Such a head (Fig. 237d), if its body is plastic, can ensure uniform sensitivity in a large range of distances.

In the control of articles of more complicated form (for instance, blanks for turbine wheels) sometimes it is advisable to anticipate in the method simultaneous resounding of the article in different directions by means of separate heads scanning the article from different sides. Scanning can be carried out from a general mechanism, which should ensure a shift with a specific interval for both heads.

In the control of large-scale articles with flat surfaces (for instance, rolled plates, large forgings) use of multichannel systems is the most advisable, allowing a scan of the whole article in one passage without reversing (by means of introducing a "scanning beam") by lines separated from one another by a defined (small) distance.

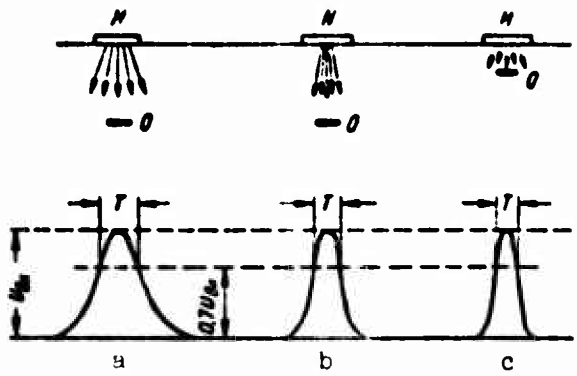

Fig. 238. Determination of scanning interval for different conditions: И – searching head; O – defect; T – step of scanning.

This distance is the scanning interval, and both in systems with a single searching head and in single-channel systems it is chosen so that it is impossible to miss a defect of assigned dimension. From Fig. 238 one may see that as the searching head advances in the direction of the arrow the amplitude of the echo signal from the flat reflector oriented perpendicularly to the field axis gradually increases from zero to maximum and then gradually drops the same way. Speed of buildup and drop of this amplitude depends on directivity of radiator, distance from it to reflector, and on dimensions of reflector. The higher the directivity of the radiator and the less the distance to the reflector, the steeper the curve of buildup and drop of amplitude of echo signal. We will conditionally assume that rejection criterion is appearance on the screen of an echo signal with amplitude ≥70% maximum amplitude of the echo signal observed on the screen when the searching head is exactly above a reflector of assigned (minimum) dimension. Then, obviously the optimum scanning interval will be equal to width of curve of amplitude change on a level corresponding to an amplitude of 0.7 maximum (Fig. 238a). With such a scanning interval a defect located between lines will give an echo signal whose amplitude will be not less than 0.7 amplitude of the echo signal from a defect of such dimension when the searching head is exactly above it.

With the same depth of bedding of a defect but higher directivity the amplitude of the echo signal is changed more sharply, and consequently the scanning interval should be decreased (Fig. 238b). Decrease of depth of bedding of defect with the same degree of directivity also leads to necessity of decreasing the scanning interval (Fig. 238c). Thus, for a given searching head possessing known directivity the optimum scan interval should be determined for defects lying at a shallow depth.

In this case, conditions of detection of defects lying "between the lines" at great depths will also be carried out. The scanning step is simple to determine on standards applied for tuning the echo-flaw detector. Analytic calculation of the scanning step is sufficiently complicated and naturally cannot be made by the formulas of Krautkrämer [226], derived on the basis of very rough approximations.

Experimental determination of the optimum scanning step for specific conditions gave the following results: for a quartz head with piezoelement 18 mm in diameter on a frequency of f = 2.5 MHz when UZK are introduced into metal through a thin film of contact lubricant the step is 6 mm; for analogous heads when diameters of piezoelements are 15 and 25 mm at 4.0 and 1.5 MHz, the step is 5 and 8 mm correspondingly.

In conditions of immersion, introduction of UZK into metal for a head with a piezoelement 20 mm in diameter on frequency 2.5 MHz the step was also 6 mm.

It is necessary to note that as a result of selection of a scanning step from the condition of 70% amplitude, there will be a certain repetition of a rejection in the control, inasmuch as echo signals forcing the automatic equipment to work will appear upon detection of a defect of assigned dimension located between the lines and several of smaller dimensions located on the line.

All considerations pertain to conditions of selection of optimum step in a direction perpendicular to direction of motion of searching heads. However, even in the selection of maximum rate of motion of heads it is necessary to consider these considerations. During the control of an article of considerable thickness, time expended by a pulse of UZK in traversing the whole acoustical channel in both sides can be so considerable that the searching head will be able to advance in a position at which amplitude of the echo signal it receives will be less than the fixed level (70%) and the defect will not be detected.

In conditions of mass industrial control of important articles usually two-phase control is employed. In the first stage — elimination control is conducted at somewhat raised sensitivity. The problem of elimination control is delay of "doubtful" articles and directing them to a repeated quality inspection. Including in the number of doubtful articles several superfluous articles does not play an essential role, inasmuch as the quality control anticipates as thorough as possible a determination of dimensions of every defect revealed during elimination control.

The whole output is not subjected to a quality control, but only a certain (usually small) part, therefore productivity is not a decisive factor and the quality control can be done manually when sensitivity of flaw detector is tuned to correspond completely to fixed norms of rejection.

Tuning on an assigned sensitivity, as also estimation of dimensions of revealed defects, as a rule is done according to special standard samples having a series of drillings of different diameter with a flat bottom. To appraise dimensions of a revealed defect on the standard will be selected a control reflector, located at the same depth as the defect and giving an echo signal of the same amplitude. Area of defect is equal to area of reflector divided by coefficient of revealability. The form of the standard sample and orientation of surfaces of introduction of UZK and axes of drillings should be selected so that introduced UZK are incident along the normal onto the flat bottom of the drilling. Upon thorough fulfillment of flat bottom and correct orientation, taking into account certain idealization of conditions of reflection of UZK it can serve as a simulated defect which is fully acceptable for tuning of sensitivity of instrument.

Certain researchers recommend type of standard more simple in manufacture in which holes of different diameter are drilled in the standard sample so that UZK drop onto the lateral surface of the cylindrical drilling in the plane perpendicular to its axis. However, as A. S. Golubev showed [227], the amplitude of the echo signal from the lateral surface of the cylinder is not uniquely connected with the diameter of the cylinder, and therefore such a standard cannot be used in adjusting the sensitivity of the echo-flaw detector.

The standard samples usually are made of the same material and in the same state of technological treatment as the controlled article. Thickness of standard is chosen equal to thickness of article. All this essentially complicates preparation and use of standards, especially in the control of articles of considerable dimensions.

While this is easy to show from equation (58), when an echo-flaw detector has a calibrated attenuator on its input, it is possible to determine area $S_Д$ of a revealed defect with respect to a standard of any thickness from any material, with control reflectors of different diameter located at any depth.

If B and $B_э$ — thickness of article and standard; r and $r_э$ — depth of bedding of defect in article, and correspondingly, control reflector in standard; б and $б_э$ — damping in material article and standard; $S_э$ — area of control reflector,

amplitude of the echo signal from which is equal to amplitude of the echo signal from the defect; and s — coefficient of revealability, then area of defect:

$$S_д = \frac{1}{s} S_э \left(\frac{r}{r_э}\right)^2 \cdot e^{2(\delta r - \delta_э r_э)} \quad (71)$$

If δ is unknown, then

$$S_д = \frac{1}{s} S_э \left(\frac{r}{r_э}\right)^2 \cdot e^{-2\delta_э r_э} \left(\frac{k}{n} \cdot e^{2\delta_э B_э}\right)^{r/B}, \quad (71a)$$

where $k = \frac{U_{дэ}}{U_{дв}}$; $n = \frac{B}{B_э}$.

If $B = B_э$, then

$$S_д = \frac{1}{s} S_э \left(\frac{r}{r_э}\right)^2 \cdot e^{2\delta_э (r - r_э)} \cdot k^{r/B}. \quad (71b)$$

If $r = r_э$, and $B \neq B_э$, then

$$S_д = \frac{1}{s} S_э \left(\frac{k}{n}\right)^{r/B} \cdot e^{2\delta_э r(n-1)}. \quad (71c)$$

If $r = r_э$ and $B = B_э$, then

$$S_д = \frac{1}{s} S_э \cdot k^{r/B}, \quad (71d)$$

And finally, if as in the usual standards, $r = r_э$, $B = B_э$ and $\delta = \delta_э$, then

$$S_д = \frac{1}{s} \cdot S_э \quad (71e)$$

(in the last case an attenuator is not required of course).

To achieve the greatest accuracy the standard must be made of a material of possessing minimum structural reverberation (and easily worked), and measurement of the amplitude of the echo signal from the defect must be made when the noise cutoff is removed.

f. Methods of Increasing the Volume of Information During Ultrasonic Control. Requirements for a High Quality Echo-Flaw Detector.

Determination of dimensions of revealed defects — the most important but not the only element of information about a defect is necessary in order to determine whether the controlled article is considered suitable or should be rejected.

Obtaining the most detailed information about a defect in essence should be the basic problem of the control as a whole and its separate elements.

If on the initial stage of development of ultrasonic flow detection all information is simple and reduces to a "yes — no" reading, then at present the

volume of information obtainable from an echo-flaw detector significantly increases and necessity of further increase of this volume causes and continues to cause continuous improvement of circuits and constructions of echo-flaw detectors.

Thus, by instrument readings supplied by the depth meter, it is possible to determine coordinates of defect with great accuracy. By increase of duration of echo signal in comparison with the bottom signal, it is possible to estimate orientation of a plane defect and to distinguish a plane defect from a volume defect. By the difference between thickness of article in the resounded section and the totality of readings of the depth measuring device during detection of a defect from two opposite sides, one can determine extent of volume defect in direction of resounding. All this presents raised requirements for accuracy and stability of work of a depth meter and for linearity of the sweep of a contemporary flaw detector.

Orientation of a plane defect may be judged also by considering the "thin" structure of the echo signal. This is possible if signals are amplified without detection. In this case interference phenomena observed during reflection of UZK from a surface oriented not at right angles to the beam lead to noticeable fluctuation of amplitude of oscillations filling the echo pulse (in detection this fluctuation is smoothed). Resolving power of instrument also increases during observation of unrectified signals — in this case on the screen between two defects located close to one another a "collapse" distinctly is seen (Fig. 239a) which on a rectified signal usually is observed only in specific cases (Fig. 239b).

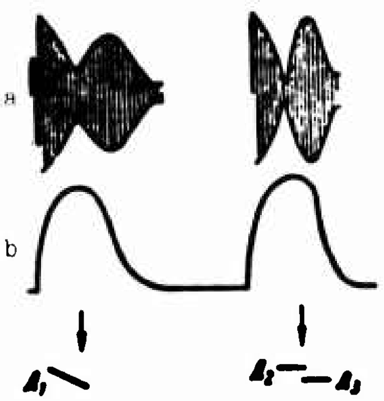

Fig. 239. Interference picture on instrument screen. $Д_1$ – defect oriented at an angle to the beam; $Д_2$ and $Д_3$ – defects located one after the other.

It is necessary to note however that appraisal of orientation of a defect by increase of duration of echo signal or by a change of its "thin structure" is possible only when UZK drop on the surface of defect at an angle not exceeding 10-20°. When angle of incidence is greater, UZK can not be reflected in the direction of the piezoconverter and the defect will not be revealed.

It is possible to increase probability of detection of such defects if we provide in the echo-flaw detector the possibility of work by the mirror shadow method. From Fig. 240 one may see that in case a, a flat defect oriented perpendicularly to the incident ray is clearly revealed in the form of an echo, and

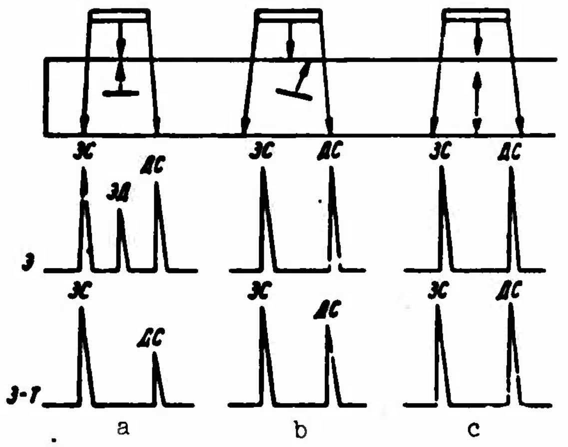

Fig. 240. Detection of a defect using the echo method (Э) and the mirror shadow method (З-Т); ЗС – sounding signal; ДС – bottom signal; ЭД – echo signal from defect.

in case b, a defect oriented obliquely is not revealed inasmuch as the reflected ray does not reach the piezoconverter. However, as is simple to understand, the total amount of energy of UZK attaining the bottom surface in both cases will be approximately identical. It will be less than in the case of absence of a defect by a certain magnitude determined by area of defect (and for an oblique defect – area of its projection onto the plane perpendicular to the incident ray). Consequently, amplitude of bottom signal in both cases (if defect is perpendicular and if it is slanted) must be less than in a faultless section (Fig. 240c). In the usual echo-flaw detector decrease of amplitude of bottom signal cannot be marked, since bottom signal as a result of large amplification as a rule is clipped.

If, however, in the circuit of the echo-flaw detector in corresponding stages there is a special deep cutoff, lowering amplification so much that the bottom signal is not clipped (echo-signal from "perpendicular" defect at so small an amplification will not be seen at all), then by decrease of amplitude of bottom signal the defect is easy to note. Defects lying in the article at considerable depth and located near the bottom surface or the surface of introduction of UZK will also be revealed.

Thus, along with channel of unrectified signal the echo-flaw detector should have a special cutoff for work by the mirror shadow method.

Use of the channel of unrectified amplification gives one more very interesting possibility of an increase of the volume of information about a defect. Phase of the first oscillation in the echo signal will be different depending upon

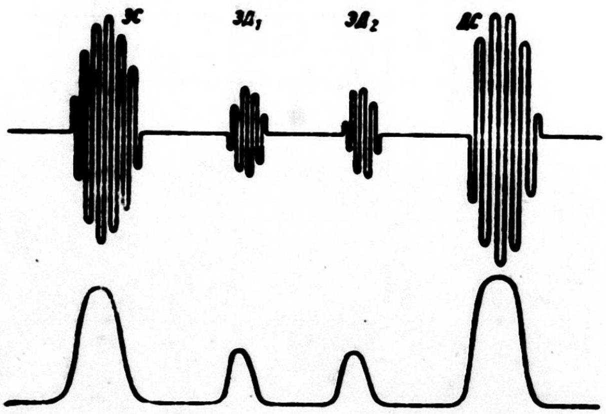

Fig. 241. Change of phase of first oscillation upon reflection from different heterogeneities of medium for unrectified (above) and rectified (below) signals: ЗС – sounding signal; ДС – bottom signal; $ЭД_1$ and $ЭД_2$ – echo signals from heterogeneities possessing different acoustic rigidity.

relationship of acoustic rigidities of media bounding the interface. If the substance filling the cavity of a defect is a medium acoustically softer than the medium on the part of which UZK are incident on the surface of the defect (for instance, air gap in metal), reflection of UZK occurs with a phase shift of 180° with respect to the incident wave.

If, however, the relationship of acoustic rigidities is inverse (for instance, inclusion of copper in aluminum, tungsten in titanium, etc.) reflection occurs in phase with the incident wave (Fig. 241).

Thus, observing polarity of the first oscillation in the echo pulse, it is possible in certain cases to obtain additional information about the nature of the revealed defect.[1]

Sometimes such additional information can play a decisive role in judging quality of the controlled article.

Thus, if in an ingot from a titanium alloy is revealed a volume defect, and by the phase of the first oscillation it was possible to establish that it is a

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[1]Here is a certain analogy with distribution of photographic density on an X-ray photograph. Depending upon whether the image of the heterogeneity revealed by X-rays is darker or lighter as compared to the surrounding background, it is possible to make a conclusion about relationship of densities of the substance filling the cavity of the defect and that surrounding it.

cavity, the ingot may proceed to further treatment by pressure. Inasmuch as melt and casting of titanium are done in conditions of special purity in the restoring atmosphere, the internal surface of the pit is not oxidized, nothing is contaminated and during pressure treatment the cavity can be completely welded.

If, however, the phase of the first oscillation turns out to be opposite, the defect obviously constitutes an inclusion of tungsten (titanium ingots, until comparatively recently were prepared by a technology which did not exclude the possibility of fragments of the tungsten electrode in melted titanium), which in further treatment of the ingot by pressure will become the origin of a fracture. The ingot therefore should be rejected, or at least the part containing the defect must be cut from it.

What has been said means that in the contemporary echo-flaw detector it is desirable to provide an unrectified signal channel for additional information about nature of defect.

However, although the importance of additional information is not decreased, most important and basic remains determination of dimensions of a revealed defect. Therefore, improvement of circuits and designs of echo-flaw detectors should be conducted on the basis of improvement and creation of new methods for determining dimensions of defect.

One of the general deficiencies of all the above methods (the basis of which are different equations for echo-flaw detector) is the use in these equations of tabular values of attenuation factor of UZK. This is the source of possible considerable errors, since the attenuation factor can fluctuate in large limits even for different sections of one article.

For more exact determination of dimensions of a defect, an equation should provide also determination of attenuation factor directly in the controlled section along the ultrasonic beam near the revealed defect.

The author in 1960 proposed a system from which A. A. Tukkayev, proceeding from wave concepts derived (in the beginning — for the immersion variant) equations enabling the use of values of attenuation factor of UZK obtained from formula (69), and exact determination of dimensions of defect.

In the immersion variant of control, in distinction from the contact method there is additional information in the form of a pulse reflected from the front edge of the controlled article. The presence of this pulse permits excluding from

the equation of the acoustic channel voltage of generator, sensitivity of amplifier and receiving transmitting properties of the searcher, i.e., the most unstable and difficultly determinable parameters of flaw detector and searcher. In deriving the equations A. A. Tukkayev used the expression for pressure in the distant zone of the sound field of a round radiator oscillating in an infinite rigid screen and loaded on a medium without shear elasticity:

$$P = i\omega\rho_{\text{ж}} a^2 V_0 \frac{e^{-ik_{\text{ж}} l}}{l} \cdot \frac{J_1(k_{\text{ж}} a \sin\theta)}{k_{\text{ж}} a \sin\theta}. \tag{72}$$

Here V_0 – amplitude of normal speed of surface of radiator, $k_{\text{ж}} = \frac{2\pi f}{c_{\text{ж}}}$ – wave number, $\rho_{\text{ж}}$ – density of liquid, J_1 – Bessel function of first order. The meaning of remaining parameters is clear from Fig. 242.

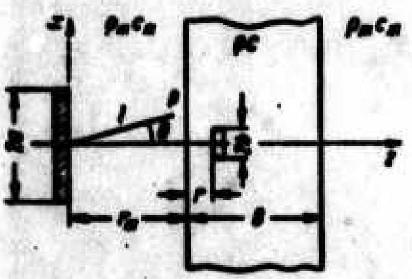

Fig. 242. Derivation of equations (73)-(75): 2a – diameter of radiator; 2b – diameter of reflector; r – depth of bedding of defect (reflector); B – thickness of controlled article; $r_{\text{ж}}$ – distance between radiator and front surface of article; $\rho_{\text{ж}}$ $c_{\text{ж}}$ and ρ_c – specific wave impedance of liquid and solid medium correspondingly.

Using this expression it is possible to calculate amplitudes A_1 and A_2 of forces on the surface of the piezoconverter, appearing due to reflection of UZK from front and rear edges of an article of plane parallel form.

Duration of the acoustic pulse is assumed such that radiation can be considered monochromatic, but standing waves do not appear. Reflectivity of UZK from interface of media is taken as not depending on angle of incidence, which is allowable inasmuch as the main part of energy of the sound field of the radiator is concentrated inside a small solid angle.

Taking into account what has been said, we calculate modulus A_1:

$$|A_1| = \pi\rho_{\text{ж}} c_{\text{ж}} a^2 V_0 R_1 \sqrt{(4-\beta_1^2)\sin^2\frac{\beta_1}{2} - \frac{1}{2}\beta_1^3 \sin\beta_1 + \frac{1}{4}\beta_1^4} \tag{73}$$

and correspondingly modulus $|A_2|$:

$$|A_2| = \pi\rho_{\text{ж}} c_{\text{ж}} a^2 V_0 R_2 e^{-2\delta B} \sqrt{(4-\beta_2^2)\sin^2\frac{\beta_2}{2} - \frac{1}{2}\beta_2^3 \sin\beta_2 + \frac{1}{4}\beta_2^4}. \tag{74}$$

In resulting expressions

$$m=\frac{\rho_{\text{м}}c_{\text{м}}}{\rho c};\quad \beta_1=\frac{k_{\text{м}}a^2}{4r_{\text{м}}};\quad \beta_2=\frac{k_{\text{м}}a^2}{4\left(r_{\text{м}}+B\frac{c}{c_{\text{м}}}\right)};$$

$$R_1=\frac{1-m}{1+m};\quad R_2=\frac{4m(1-m)}{(1+m)^2}.$$

Ratio of amplitudes of echo signals from front and rear edges on screen of flaw detector is identical to ratio of amplitudes $\frac{|A_1|}{|A_2|}$ of forces on surface of piezoconverter, therefore measurement of the ratio of electrical signals using a flaw detector attenuator calibrated in nepers gives the quantity ln $\frac{|A_1|}{|A_2|}$.

During calculation of amplitude of force on surface of piezoconverter (A_3), caused by reflection of UZK from defect (considering that only a quantitative appraisal as a rule is required by defects of small dimensions), it is advisable to use expression (72), valid along axis of radiator and very exact in neighborhood of axis at distance of the order of wavelength.

Calculating amplitude A_3 and dividing it into the earlier calculated value of A_1, we obtain the equation determining dependence of ratio of amplitudes of forces on surface of piezoconverter caused by reflection of UZK from front edge of article and from defect (or, which is the same – ratio of amplitudes of corresponding echo signals on screen of flaw detector) on dimensions of defect, depth of bedding, frequency of UZK, coefficient attenuation factor in metal, etc.:

$$\frac{|A_1|}{|A_3|}=\frac{1-m^2}{4m}\cdot\frac{a^2}{b^2}\cdot e^{2\delta r}\times$$

$$\times\frac{\sqrt{(4-\beta_1^2)\sin^2\frac{\beta_1}{2}-\frac{1}{2}\beta_1^3\sin\beta_1+\frac{1}{4}\beta_1^4}}{\sqrt{1-4\gamma J_1(\gamma)\cos\alpha+4\gamma^2J_1^2(\gamma)}}\times$$

$$\times\frac{1}{\sqrt{(4J2x_1\alpha+\alpha_1^2)\sin^2\frac{\alpha}{2}-\frac{1}{2}\alpha_1^2\alpha\sin\alpha+\frac{1}{4}\alpha_1^2\alpha^2}} \tag{75}$$

Determining attenuation factor δ by formula (69), from equation (75) one can determine radius of reflector, for which it is necessary to find ratio ln $\frac{|A_1|}{|A_3|}$ by the attenuator and determine distance $r_{\text{м}}$ to front edge and depth of bedding of reflector r by the depth guage.

Determination of radius of reflector is considerably simplified if attenuation factor δ is preliminarily determined, and by formula (75) the graph depicted in

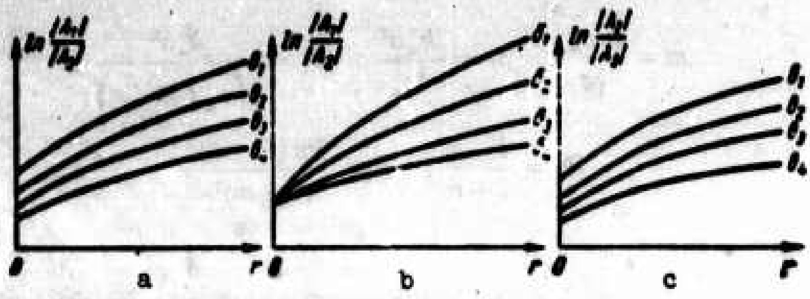

Fig. 243. Ratios of amplitudes of echo signals depending upon different factors: a – echo signals from A_1 and A_3 (A_1 – front edge, A_3 – reflector) depending upon depth of bedding of reflector for different b (b – radius of reflector): $b_1 < b_2 < b_3 < b_4$; b – echo signals from A_1 and A_2 (A_2 – bottom edge) depending upon B at different δ: $\delta_1 > \delta_2 > \delta_3 > \delta_4$; c – echo signals from A_2 and A_3 (A_2 and A_3 – infinitely extended plane and reflector located at the same depth under the surface of introduction of UZK) depending upon depth for different: $b_1 < b_2 < b_3 < b_4$. Scale along the vertical is logarithmic.

Fig. 243a is constructed, showing dependence of ratio $\ln \frac{|A_1|}{|A_3|}$ on depth of bedding of reflector (r) at different radii. For determination of radius of reflector it is necessary to determine $\ln \frac{|A_1|}{|A_3|}$ by the attenuator, and by the depth meter – r. The desired radius will correspond to the curve on which will lie the point with coordinates $\left[\ln \frac{|A_1|}{|A_3|}, r\right]$.

If articles with grain of various magnitude are subjected to control, the magnitude of the attenuation factor on different sections of the same article can be different and the presented method of appraisal of dimensions of defects calculated on constant δ can give large error. To decrease error attenuation factor δ it is necessary to measure close to the revealed defect. In this case it is necessary to construct graphs depicted in Fig. 243b, c. The curves in Fig. 243b give the dependence of ratio $\ln \frac{|A_1|}{|A_2|}$ on distance r = B between edges at different values of attenuation factor.

Value $\ln \frac{|A_1|}{|A_2|}$ is obtained from formula (69).

Curves in Fig. 243c give dependence of ratio $\ln \frac{|A_2|}{|A_3|}$ on depth of bedding of reflector at different values of radius of reflector, where amplitude (A_2) of the echo signal from the bottom edge with the help of graph Fig. 243b is recalculated

on depth r, which excludes dependence of ratio $\ln\frac{|A_2|}{|A_3|}$ on coefficient of damping. Expression $\ln\frac{|A_2|}{|A_3|}$ is calculated by the formula

$$\frac{|A_2|}{|A_3|}=\frac{a^2}{b^2}R_1\times$$
$$\times\sqrt{\frac{(4-\beta_2^2)\sin^2\frac{\beta_2}{2}-\frac{1}{2}\beta_2^3\sin\beta_2+\frac{1}{4}\beta_2^4}{[1-4\gamma J_1(\gamma)\cos\alpha+4\gamma^2J_1^2(\gamma)]}}\times$$
$$\times\sqrt{\frac{1}{\left[(4-2\alpha_1\alpha+\alpha_1^2)\sin^2\frac{\alpha}{2}-\frac{1}{2}\alpha\alpha_1\sin\alpha+\frac{1}{4}\alpha_1^2\alpha^2\right]}} \qquad (76)$$

Appraisal of dimensions of revealed defect in a material with a conserted structure is made in the following order:

1. The ratio $\ln\frac{|A_1|}{|A_2|}$ is determined by flaw detector attenuator, and thickness B of the article in direct proximity from the detected defect is determined by depth meter.

2. By the graph Fig. 243b magnitude of δ is found.

3. Depth of bedding of defect (r) is measured, and then by Fig. 243b, corresponding to the found attenuation factor, the ratio $\ln\frac{|A_1|}{|A_2|}$ is determined for a thickness of article equal to depth of bedding of defect, i.e., $\ln\frac{|A_1|}{|A_2|}$ is determined for a bottom echo signal, recalculated on depth of bedding of defect.

4. By instrument attenuator the ratio $\ln\frac{|A_1|}{|A_3|}$ is measured.

5. Calculate the difference:

$$\ln\frac{|A_1|}{|A_3|}-\ln\frac{|A_1|}{|A_2|}=\ln\frac{|A_2|}{|A_3|}.$$

6. With help of found values of r and $\ln\frac{|A_2|}{|A_3|}$ by the graph Fig. 243c radius of equivalent reflector is determined.

Dimension of real defect is determined by dividing dimension of equivalent reflector by coefficient of revealability.

It is necessary to note that error during appraisal of dimensions of defects increases if along the beam there are zones with different magnitude of grain.

The presented variant as was noted above, has been developed in reference to the immersion variant of the echo method. However, this method can be successfully

used for the contact variant, if dimensions of defect revealed by the usual searching head are determined by another measuring head of special construction.

In the work of an ordinary searching head condition on which the described method is based are not fulfilled.

a. Amplitude of the pulse reflected from the front edge of a controlled article cannot be measured, since this pulse is not separated in time from the sounding pulse.

b. Transmission coefficient of energy of UZK through a layer of contact lubricant depends on thickness of this layer, changes at a change of pressure on searching head, and consequently, cannot be considered.

c. In the controlled article at a certain depth the near zone of the radiator field spreads; within the limits of this zone derived equations cannot be used.

A special measuring head should divide the sounding pulse and the pulse reflected from the front edge of the controlled article to ensure constancy of transmission coefficient of energy of UZK through a layer of contact lubricant and possibility of using equations calculated on the distant zone of the radiator field for determination of dimensions of defects located at any depth under the surface of introduction of UZK.

Such a head, developed by the author and A. A. Tukkayev, is shown schematically in Fig. 244. In this head piezoelement 1 is rigidly glued to aluminum cylinder 2, playing the role of a delay line. Length of this cylinder is chosen so that it includes the whole near zone of the radiator field. Diameter of cylinder should be sufficient so that outermost rays of the beam of UZK are not reflected from its lateral surface. On upper base of cylinder are hemispheric scatterers, decreasing intensity of repeated reflections of UZK. Steel cup 3 is screwed to the cylinder; in the walls are channels 4 for supply of contact lubricant. As the cup rotates, resting on its pointed bottom on the surface of a flat plate, the cylinder moves upwards, and between the contact surface of the cylinder and the surface of the plate will be formed an adjustable gap whose magnitude is read by scale 5 on the cylinder. The gap should be small, for instance 0.05-0.1 mm. After adjustment of gap, stopper screws 6 are fixed, the head is placed on the surface of the controlled article exactly above the revealed defect, through channel 4 the gap is filled with oil. Dimensions of defects are determined just as for the immersion variant. Transmission coefficient of energy of UZK is determined by curves Fig. 86,

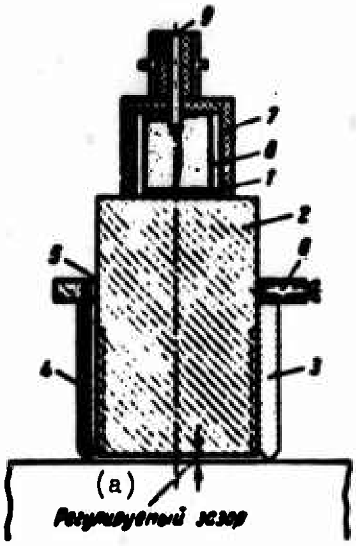

Fig. 244. Measuring head for determination of dimensions of defects during use of contact variant of echo method: 1 – piezoelement; 2 – metallic cylinder; 3 – cup; 4 – channels for supply of contact lubricant; 5 – ring with sight for scale reading; 6 – stopper screw; 7 – cap; 8 – damper; 9 – contact.
KEY: (a) adjustable gap.

proceeding from magnitude of gap and frequency of UZK for a "cylinder material – oil – material of controlled article" system.

The proposed method for determination of dimensions of defects has been experimentally checked in control by the echo method using the new (described below) instrument [DUK-6V] (ДУК-6В) on samples of steel [EI481] (ЭИ481) and aluminum alloy D16. Defects were created by drilling; every defect had a flat header located at a depth of 60 mm. Frequency of ultrasonic oscillations was 1.5 MHz, diameter of radiator 25 mm, distance ($r_{ж}$) to front edge 200 mm. Data of experiment, shown in Fig. 245, showed that theoretical and experimental results coincide sufficiently satisfactorily.

Thus, for appraisal of magnitude of defect during control of articles from a given material with the help of a flaw detector with calibrated adjustment of amplification, it is necessary to have two families of curves which can be constructed beforehand for all controlled materials.

For fullness of characteristics of the given method of calculation of the acoustic channel of the flaw detector, we will note that the possibility of disregarding transformation of longitudinal waves into shear was justified by I. N. Yermolov in deriving equations for the echo-flaw detector. In our case this disregard is justified in still larger degree due to the large dimensions of the radiator (and consequently, large directivity of beam of UZK). A certain deficiency of calculation is identification of reflector with piston in rigid screen, which can become the source of possible errors. Error can appear also due to reflectivity of UZK from bottom surface of controlled article being taken as constant, whereas it can fluctuate in certain limits, depending upon thoroughness of treatment of surface. However, advantages of the proposed method recompense these

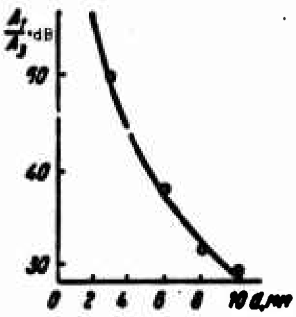

Fig. 245. Dependence of ratio $\frac{A_1}{A_0}$ on diameter of reflector (d). Data from calculation (solid line) and experiment (circles).

deficiencies.

The method permits a quantitative solution of complicated problems appearing during ultrasonic control of large blanks. For instance, it is required to determine minimum dimension of defect which can be revealed in a large scale blank near the bottom edge during resounding on one side. For this the absolute value of amplitude A_1 of the echo signal from the front edge is determined (in volts). This can be done, for instance, knowing amplification factor of receiving channel and sensitivity of the electron beam tube, or by using a special measuring instrument — the pulse microvoltmeter. Then, measuring with an attenuator, the ratio of A_1 to A_2, we determine A_2. Further, setting the (necessary for clear detection of defect) excess of amplitude of echo signal from defect above amplitude of noises, we determine minimum magnitude of A_3, after which find the ratio of A_2 to A_3, and for the given distance we determine minimum diameter of reflector.

In practice even more complicated problems are met: for instance, it is necessary to conduct ultrasonic control of large scale blanks made a material with large attenuation factor. The bottom signal in this case is not observed. Usually production workers solve this problem by consecutive resounding of a blank from two sides in opposite directions. Here it is assumed that a sensitivity is ensured which is sufficient for detection of defects of assigned minimum dimension at a depth somewhat exceeding half the height of the blank, and consequently in control from two sides — the whole volume of the blank is checked.

Meanwhile sensitivity can be insufficient; the middle part of the blank is not checked. A correct solution of this problem requires determination of attenuation factor of UZK in the given material on a templet cut from the blank. After that, for an assigned diameter, knowing absolute values of A_1 and A_3 and attenuation factor δ, by the graph Fig. 243c it is possible to solve the problem with respect to distance.

As can be seen from given examples, with such a method the bottom signal as the basic criterion of energy content introduced in the pulse of UZK loses value. It is more simple and correct to determine energy relationships and to choose conditions of control using as a criterion amplitude of the echo signal from the front edge of the article. Obviously, for rapid and exact measurement of this amplitude in the receiving channel it is advisable to provide a corresponding instrument allowing direct measurement without any calculations.

An advantage of the proposed method is that it permits an approach to solution of the problem of automation of control. All automatic signalling apparatuses of defects, including the [ASD] (АСД), created for work with the echo-flaw detector V4-7I, operate at the appearance of an echo signal whose amplitude is higher than the assigned value and which is located in a defined time interval between echo signals from front and bottom edge. The dependence of amplitude of echo signal on depth of bedding of defect is not considered, and therefore in tuning to a "distant" defect an over rejection will be observed, and in tuning to a "near" defect – an underrejection. For a specific article from material with a defined value of attenuation factor, in principle it is possible (although very difficult) to carry out automatic time gain control at which amplitude of echo signal does not depend on depth of bedding of defect. However, such is not very practical, since law of change of amplification from time will change during control of articles with different attenuation factors.

The most regular problem is creation of an automatic signalling apparatus of defects in whose circuit is an analog computer. It should determine with respect to the relationship of amplitude echo signals from front and bottom edges of article and time distance among these echo signals the attenuation factor of UZK in the controlled section, and proceeding from obtained data, the amplitude of the echo signal from a defect of assigned dimensions depending upon depth of its bedding.

The formulated requirements for a high quality arbitration instrument were in certain degree considered in the development[1] of the circuit and construction of the pulse echo-flaw detector DUK-6V.

The ultrasonic pulse echo-flaw detector DUK-6V (Fig. 246), intended for work in contact and immersion variants of the echo method, has the following basic technical characteristics.

Working frequencies – 4, 2.5, 1.5 and 0.7 MHz. These frequencies were selected in accordance with curves Fig. 193 and ensure optimum sensitivity during control of articles from deformed steel and aluminum alloys up to 1 m thick. Lowest frequencies (1.5 and 0.7 MHz) permit controlling metallic articles of average thickness with

[1]Circuit and construction of instrument were developed in 1961-1962 under the leadership of the author B. G. Golodayev; V. I. Minakov, Yu. V. Lange, A. A. Tukkayev, Z. I. Manayevoy, N. V. Babkin, S. V. Veremeyenko.

high level of acoustic noises and also articles from plastics and rubber a few centimeters thick.

The instrument provides smooth frequency control on every range within the limits of ±10% from rated.

Minimum depth of detection of defects (dead band) during work of a combined searching head without application of compensation for different frequencies in the contact variant is:

Depth, mm	Frequency, MHz
5..........	4
6..........	2.5
15..........	1.5
40..........	0.7

During work in the immersion variant the magnitude of the dead zone, as a result of using a circuit for electrical compensation of free oscillations permits reducing dead zone at frequencies 1.5 and 2.5 MHz to 5-3 mm correspondingly.[1]

Maximum range of measurements of distances to defects and thickness of article is 2.5 m for materials with a rate of propagation of UZK of 2500-6500 m/s.

The amplification factor on all frequencies is not lower than $2 \cdot 10^6$, amplitude of oscillations on the leadout of the radio impulse generator at minimal pulse duration not less than 1000 V, and at maximum reaches 2800 V, which in combination with use of piezoelements from highly effective materials ensures very high sensitivity of instrument.

Amplifier of instrument has a time adjustment of sensitivity [VRCh] (ВРЧ). Duration of VRCh is regulated by degrees from 30 to 8000 μs, depth of VRCh is from 0 to 35 dB.

For quantitative measurement of ratio of amplitudes of echo 6 signals. The amplifier has an attenuator with step-wise and smooth adjustments within limits of 0-60 dB. Because there is in the amplifier a special unrectified signal channel the instrument permits observing on screen of indicator rectified and unrectified

[1]Use of a special amplifier developed for the DUK-6V according to the circuit proposed by B. G. Golodayev, Author's certificate No. 149934 USSR, 1961), providing undistorted amplification of a maximally short pulse, after filling with oscillations of super-high (hundreds of MHz) frequency, should reduce dead band approximately to a duration of a half-period.

echo signals.

The instrument has automatic signaling apparatus of defects [ASD] (АСД) upon detection of defects in articles of simplest forms a light signal is activated. For control of articles of large thickness the instrument provides the possibility of working with a scan delay. Magnitude of delay is regulated within limits of 10-1000 μs. The sweep time when working with a delay is regulated in the same limits as when working without a delay.

The instrument is completed by wear-resosting searching heads possessing raised parameters. The possibility of working wit special search heads having built-in inductance coils is provided also.

Industrial testing samples of the DUK-6V produced by the SKB UZD completely corroborated the correctness of all considerations underlying its development.[1]

High exploitational qualities of the instrument led to ideas about necessity of creating an echo flaw detector possessing approximately the same data but more compact, designed for using in workshop conditions.

Such an instrument, the DUK-5V, was developed in the SKB UZD[2] and is designed so that certain units provided in the DUK-6V can be carried in special attachments connected to the instrument in necessary cases. An unrectified signal channel in the amplifier is not provided. The remaining indices are approximately the same as in the flaw detector DUK-6V. In design the DUK-5V is by far more compact, and in weight — approximately half as much as the DUK-6V. A general view of the DUK-5V is given in Fig. 247.

With the mastery of production of the DUK-6V and the DUK-5V with attachments, our industry obtains completely modern high-quality equipment, making it possible to solve complicated problems appearing in practice.

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[1]The DUK-6V has been put into serial production at the "Precision Electrical Instruments Plant".

[2]The DUK-5V, developed by V. A. Tokariv, will be manufactured by the "Precision Electrical Instruments Plant" under another brand name.

VII

ULTRASONIC CHECK OF METALLIC BLANKS, SEMIFINISHED PRODUCTS, AND ARTICLES

Practice of domestic and foreign ultrasonic flaw detection shows that its possibilities are very wide; however, in order to obtain the needed effect one should approach every specific problem while taking into account all data on properties of material, technology of manufacture of the checked article, character and dimensions of possible defects.

With such an approach, even with the aid of standard flaw detectors of industrial types frequently the solution of problems, considered insoluble until recent time, turns out to be possible.

a. Check of Casting

It is accepted to consider that ultrasonic methods of control are ineffective for check of intricate-shape casting. Indeed, complex shape of castings, poor quality of surface, coarse-grained structure, difference in magnitude of grain between core and peripheral zones in thick sections, difference in magnitude of grain between thick and thin sections — all this strongly hampers check and practically excludes the possibility of its automation. If, moreover, we add that cracks emerging on surface of casting can be revealed by capillary and sometimes — magnetic methods, for revealing some of only the internal defects the use of ultrasonic methods should be recognized as little effective economically. However, if for intricate-shape castings from light alloys for this purpose it is possible to apply radioscopy with X-rays, cast iron and steel castings of considerable thickness are already X-rayed with difficulty.

Works of various researchers, carried out mainly in West Germany [FRG] (ФРГ) [48], showed that at thorough preparation of method and technology of inspection of castings from carbon steel and cast iron fair results can be obtained in a number of cases. Thus, at frequencies 0.5-1.0 MHz it is possible to reveal rough flow holes in iron castings with thickness up to 100-150 mm. Steel casting (including pipes cast by centrifugal method) can be checked with thickness up to 50-80 mm. With this it is possible to use longitudinal and shear ultrasonic oscillations [UZK] (УЗК), introduced at an acute angle to surface of article. In the latter case because of poor quality of surface the best acoustic contact is obtained if the body of searcher head is made from rubber instead of organic glass.

It is also possible to measure wall thickness of cast-iron and steel castings if the searcher head is equipped with a piezoelement of high sensitivity with small contact surface. Figure 248 shows how wall thickness of complex iron casting is measured in a difficultly accessible place — with the aid of a head with specially designed holder.

Nevertheless, as compared to check of intricate-shape casting the use of ultrasonic methods for inspection of ingots, subjected to treatment by pressure, is more effective for the purpose of detection of rough defects in them. For such ingots from various metals and alloys, intended for manufacture of semifinished products and articles of critical assignment, relatively large dimensions, simple shape (cylinder, right-angle parallelepiped), very uneven surface, and coarse-grained structure are usually characteristic. The latter, especially in ingots from metals possessing considerable elastic anisotropy, leads to intense damping of UZK because of their scattering with grains of metal and to a high level of structural reverberation. Therefore, for the purpose of increase of breakthrough ability and also for the purpose of increase of ratio of useful signal to reverberation interferences ($U_{вх}/U_{а.ш}$) it is necessary to conduct the check on an UZK of lowered frequency (0.25-1.0 MHz). Hence it follows that during inspection of ingots, especially large sized, sensitivity and accuracy of determination of coordinates of defects is low.

However, high sensitivity is usually not required in these cases: basic defects, which should be revealed (blowholes, large pores, zones of friability, foreign inclusions, and hot cracks), have rather large dimensions. All these defects, besides cracks, are volume and therefore (and cracks because of

considerable roughness of their surface) are reflected well by UZK, incident from any direction, and can be revealed when sounding from different sides.

Steel ingots can be sounded to a depth about 1 m at 0.25 MHz frequency. However, in order to more precisely determine coordinates of defects, it is better, where this is possible, to use frequency 0.5 MHz. In a number of cases inspection conditions are improved after application of homogenizing annealing of ingots.

Ingots from alloy steel are sounded considerably worse because of intense of damping UZK. Ingots from aluminum and titanium alloys can be checked at frequencies 0.5-1.5 MHz to a depth over 1 m. Ingots from zirconium and molybdenum with up to 300 mm diameter and up to 1 m height are sounded well at frequency 1 MHz, and small ingots from hafnium – at frequency up to 5 MHz. Tungsten ingots are checked excellently at frequencies up to 5 MHz with high sensitivity, since elastic anisotropy is absent for tungsten and there is no structural reverberation. Elastic anisotropy highly impedes check of ingots from nickel alloys, brass, and bronze (here there is also shown intense damping of UZK).

Possibilities of ultrasonic check of cast plates and rods from uranium are limited still more, considerable elastic anisotropy of which [115] combined with coarse grain size leads to so strong a scattering of UZK that maximum thickness of checked section cannot be higher than several centimeters.

Check of ingots can be conducted by the echo-method with the aid of a combined searcher head. Application of mirror-shadow method with the use of separate heads is also very expedient. During work at low frequencies (0.5 MHz) the divergence of beam of UZK is so considerable that axes of heads can be oriented along the normal to surface of ingot (Fig. 249).

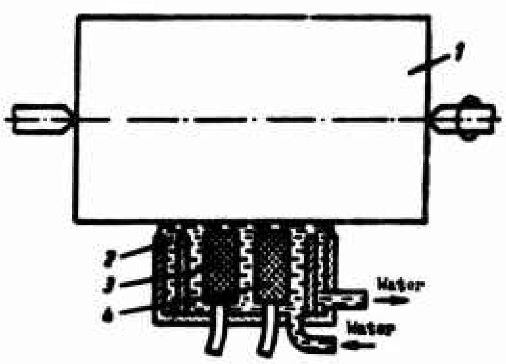

Fig. 249. Diagram of ultrasonic check of large sized ingot with the aid of separate-combined head with jet contact (A. P. Saltykov): 1 – ingot; 2 – meniscus; 3 – radiating head; 4 – receiving head.

In most cases the surface of ingots from light and special alloys is subjected to treatment before plastic deformation. Therefore, in many cases it is possible to apply the contact echo-method. It is more reliable, however, to use immersion, and sometimes – jet contact. It is convenient to conduct sounding of flat ingots by means of scanning with lines in the direction of thickness of ingot. Sounding of cylindrical

ingots can be carried out either on the end face along the axis or, which is more reliable — on the side of lateral surface along the diameter. Inasmuch as divergence angle of UZK is great, scanning along helix is not required. It is sufficient to pass the head 4-6 times along generatrix of cylinder, turning the ingot 90-60 degrees after each pass. Thus, sufficient productivity of check can be attained. With such a check rough hot cracks are completely reliably revealed (Fig. 250). Blowholes and zones of friability are revealed well also. During detection of blowholes in ingots from metals smelted in a neutral or reducing atmosphere, it should be considered that internal surfaces of such blowholes are not oxidized and can be sealed during further treatment by pressure. Such blowholes are not rejecting criterion. Rejection of ingots containing rough cracks permits increasing the quality of semifinished products, produced in the process of further deformation.

However, inasmuch as in process of deformation, as was shown above (p. 36), various defects can also be formed, ultrasonic check of deformed semifinished products has decisive value for increase of quality of production.

b. Check of Forgings

Check of forgings (especially large sized) is one of the most effective applications of ultrasonic flaw detection. Blanks of turbogenerator rotors having diameter about one and a half meters and weighing tens of tons, blanks of large dies ("blocks"), having weight of the same order, blanks of turbine and compressor disks for gas-turbine engines, and forgings from light alloys for aircraft parts can be checked by ultrasonic methods for the presence of flakes, liquation accumulations, zones of friability, residue of shrinkage cavities, slag, nonmetallic, and foreign inclusions, forging cracks, internal ruptures, stratifications, oxide films, zones of coarse granularity, and others. Structure of metal of forgings considerably differs from structure of ingot; therefore, metal underwent some deformation. Grains of metal of forging are stretched in the direction of flow, which determines orientation of many defects. Scattering of UZK was decreased, which permits "piercing" the thickness 1-2 m at frequency 0.5-1 MHz.

Construction of turbogenerator rotor usually provides for the presence of a through channel with several centimeters diameter, oriented along the axis of

rotor. This channel permits carrying out visual inspection of internal surface with the aid of periscopic devices and to some degree estimating the quality of metal in the central zone of forging affected the most wieh defects. Before the introduction of ultrasonic check of rotors this inspection was the only form of nondestroying check of rotor quality.

With ultrasonic check (usually at frequency 2 MHz) the surface of channel permits receiving a "bottom" echo signal, which facilitates conditions of sounding inasmuch as it is necessary "to pierce" only about half the diameter of rotor. Check operation is usually conducted after machining the rotor to $\nabla 5 - \nabla 6$, while it is possible to conduct the check in process of machining. At the shown cleanness of treatment the check is easily executed by contact echo-method (Fig. 251). Searcher head is pressed with the aid of an attachment permitting regulation of pressure on head. This attachment (Fig. 252) is fastened in support of machine, which permits carrying out scanning along helix with necessary spacing (~10-15 mm). Contact lubricant is continuously fed from a special tank, also installed on support.

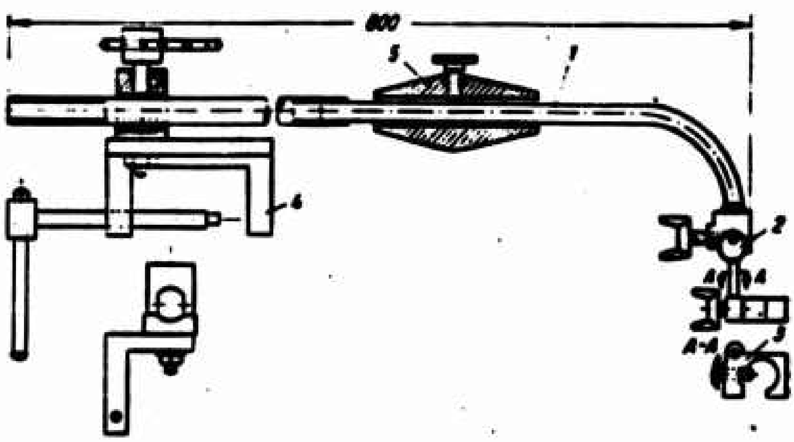

Fig. 252. Attachment for clamping the searcher head to surface of checked rotor [245]: 1 – lever; 2 – ball joint; 3 – clamp for searcher head; 4 – clamp for fastening attachment to support of machine; 5 – moving load, regulating clamping force of head.

Check of rotors is widely applied in domestic [245] and foreign [246, 247, 248] turboconstruction, making it possible to ensure high quality of released turbogenerators. According to the "Elektrosila" plant, from 223 pieces of checked rotors weighing 3-65 t, 6 rotors were rejected because of the presence of flakes and cracks. Such defects are very dangerous in a rotor revolving at up

to 3000 r/min [4]

Check of blanks for large dies is no less effective. These blanks, weight of which reaches several tens of tons, are manufactured from special steels, alloyed with scarce metals, and subjected to very complicated and expensive machine and manual treatment for manufacture of "impression" of die. If preliminarily subject the die "block" to ultrasonic check at frequency 1-2 MHz, it is possible to detect internal defects, determine their coordinates, and either reject the "block" or conduct treatment of die so that defective zone would be removed, defects would not emerge to surface of finished "impression," and consequently, the die would not turn out to be unsuitable. For reliable check of die "block" we should treat (planing, milling) two - three of its mutually-perpendicular surfaces (with cleanness ▽4-▽5) and subject the block to ultrasonic check in two or three directions. Such double or triple check, although it is less productive and requires expenditure on preparation, in return permits determining location of defective zones more exactly. Such a check is also completely justified economically, inasmuch as the cost of the almost finished die, which it is necessary to reject if defects emerge to surface of "impression," is very great.

It is necessary to note that check of die blanks has not yet received the propagation in industry that it deserved. Such a position can be explained by underestimation of the large economic effect which can be obtained from wide introduction of this check. Inasmuch as a die is only a tool, and not production supplied to consumer, its value is not reflected on operational characteristics of articles manufactured with the aid of this die.

In cases when ultrasonic check helps to increase operational characteristics of articles, it is more widely applied by producers according to customer's requirement, as can be seen from the preceding example with rotors.

Ultrasonic check is still more widely used for increase of quality of such articles, whose failure in operation can lead to accidents with human victims. Customer requirements and producer responsibility in these cases are very high, which justifies one hundred percent ultrasonic checking even if additional essential significant expenditures are necessary for this. As an example it is possible to cite check blanks for parts of gas turbine aircraft engines.

Fig. 253. Stratification in forged blank from heat-resisting alloy.

Forged blanks from heat-resisting alloys for stamping of turbine and compressor disks are represented by cylinders of irregular shape (so-called "washers") with diameter up to 1 m and height in several tens of centimeters.

Degree of deformation of these blanks is comparatively small; therefore, along with stratifications, characteristic for deformed metal (Fig. 253), and also with slag and nonmetallic inclusions in them there are frequently encountered unsealed shrinkage cavities and pores (Fig. 254). Orientation of these defects can be different, from which it follows that for increase of reliability it is desirable to produce the check in two directions from end faces, parallel to axis of blank, and from lateral surface, along radius. The echo-method in contact and immersion variants is the most effective. Contact variant requires treatment of surfaces of introduction of UZK with cleanness not less than $\nabla 5 - \nabla 6$. Such cleanness of treatment can be reached by finishing, and on flat surfaces – ironing in the last operations of forging with application of polished lining under the striker. Check is conducted most frequently at frequency 2.5 MHz; however, large sized washers, and also those manufactured from alloys with large attenuation factor and high level of noises (for instance from certain alloys on a nickel base), should be checked at lower frequencies (1.5 MHz and less).

As a result of the effect of enumerated factors, when checking washers sensitivity is obtained understated, and the smallest defects (impermissible in finished disks) are often not revealed. Therefore, check of washers should be considered preliminary, intended for detection of the roughest defects. Shallow defects should be revealed during repeated check – in stampings or in finished disks. Sensitivity with such obligatory repeated control, generally speaking, is higher than during check of washers, inasmuch as noise level is lower. For

this reason a volume defect, area of reflecting surface of which is not changed during stamping (for instance solid inclusion), will be revealed better than in washer. If, however, the area of reflecting surface of volume defect during stamping becomes larger (for instance when flattening a blowhole), sensitivity increases by two causes – as a result of lowering the noise level and increase of reflecting surface. If in the forging there was stratification of a small area, during stamping its area is practically not increased, but the opening can be decreased significantly (pressing of stratification will occur), as a result of which it will be considerably more difficult to reveal this stratification. In an extreme case stratification can be sealed completely and will not be revealed at all; however, such a case not dangerous – in fact the defect no longer exists.

During check of large forgings from aluminum alloys along with the enumerated defects the detection of thin oxide films is a very important problem. As was already indicated earlier, revealability of such a defect is very low because of small difference of values of specific wave impedance of aluminum and aluminum oxide. In order to reveal oxide films such an increase of frequency of UZK is necessary that it turns out to be impossible for articles of considerable thickness. Thus, for production of noticeable reflection from aluminum oxide film of 0.05 mm thickness it is required, as calculation by formula (40) shows, to increase frequency of UZK to ~50 MHz. This is explained, along with the already noted proximity of values of specific wave impedances of aluminum oxide and aluminum, also by high rate of propagation of elastic oscillations in it (c = 10,000 m/s). However, with intense plastic deformation of metal, for instance during stamping, due to the considerable difference of plastic properties of aluminum and aluminum oxide gaps can be formed (deformation stratifications) between surface of oxide film and the surrounding metal, facilitating detection of this defect. These gaps are increased after heat treatment, which leads to additional increase of revealability factor of oxide films; in this case at frequency 2.5 MHz this factor is equal to ≈0.25-0.3.

Inasmuch as with repeated check there is no complete confidence in detection of all defects, check of forgings should be conducted very thoroughly without any allowances for forthcoming check of stampings and finished articles.

In distinction from check of ingots, during check of large forgings it is

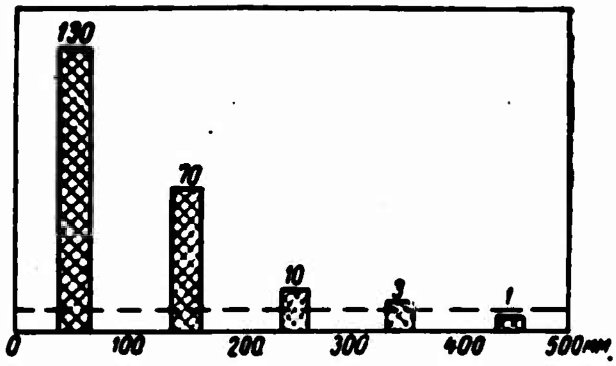

Fig. 255. Distortion of results of check when sounding a large blank without application of VRCh. Number of "defects" sharply increases in proportion to approach to surface of introduction of UZK. Dotted line shows quantity of defects revealed during layer check (layer thickness — 100 mm) with use of VRCh.

required not only to reveal large defects, but also to reveal defects of small dimensions and to estimate these dimensions. In these conditions it is necessary to especially thoroughly consider the sharp drop of sensitivity with increase of depth of occurrence of defect. Thus, with thickness of forging 0.5 m the ratio of amplitudes of echo signals from defects of equal area, located at minimum and maximum depths, turns out to be over 1000. This can lead to absolutely incorrect results of check. When adjusting the check reflector located at bottom surface, the quantity of defects revealed in the layer adjacent to surface of introduction of UZK is extremely great. In Fig. 255 there are given results of check of forging 0.5 m thick from aluminum alloy.

Number of recorded defects at a different distance from surface of introduction of UZK composes:

Distance, mm	Number of defects, pieces
0-100	130
100-200	70
200-300	10
300-400	3
400-500	1

In the opposite direction the picture is reversed: in the layer in which 1 defect was noted, there is recorded 129, and in the layer where 130 defects were noted, not one is recorded. Total amount of noted defects in both cases is approximately equal.

These results indicate the presence of "supersensitivity" in the layer adjacent to surface of introduction of UZK. With such supersensitivity echo signals of considerable amplitude can be obtained from the smallest structural heterogeneities, not being rejection criterion. So that the check would permit revealing defects of assigned dimension, it is necessary to make sensitivity

identical with respect to depth. It is possible in principle to equalize amplitudes of echo signals from defects lying at a different depth by using intermittent adjustment of amplification factor; however, for the considered example the depth of such adjustment should be greater than 60 decibels, and this is difficult to carry out. Therefore, in the future before creation of systems with a computer, which considers the dependence of amplitude of echo signal from depth of occurrence of defect, there should be recommended a layer check with use of delay of scanning and intermittent adjustment of amplification factor. With layer check adjustment at first is produced on the layer that is most remote from the surface of introduction of UZK, during check of this layer do not take into account echo signals appearing on the instrument screen in the left part of scanning – from heterogenities lying in layers located closer. After checking the distant layer (front boundary of layer is marked on scan of moving mark of depth gauge) the instrument is adjusted according to standard of smaller thickness (with check reflector of the same diameter) on the next adjacent layer, lowering sensitivity (quantity and amplitude of unrecordable echo signals in left part of scan are decreased). There is conducted check of this layer, then the instrument is readjusted to the next layer (sensitivity of instrument is lowered still more) and thus (with layers of thickness about 100 mm) the entire forging is checked. Within the layer of 100-150 mm thickness equalizing of amplitude of echo signals from equivalent defects located at a different depth can be carried out at depth of adjustment available in industrial echo-flaw detectors and equal to 30-40 dB.

However, only a [DUK-6V] (ДУК-6В) instrument permits carrying out delayed intermittent adjustment of sensitivity and equalizing sensitivity within limits of 100-150 mm layer, located at any depth in article of >500 mm thickness. (In other instruments intermittent adjustment of sensitivity can be carried out only at a depth of ≤50-80 mm from surface of introduction of UZK.) With such layer check in a forging, analogous to above mentioned, with the same adjustment there is revealed 6-8 approximately identically sized defects located at a different depth, structural heterogeneities are not noted.

It is possible to determine dimensions of revealed defects by comparing them with check reflectors in standards, or by calculation, for which it is necessary to measure U_{BX}. In both cases a more exact result is obtained at great depth of

occurrence of defect, inasmuch as in this case the defect is seen from the point of location of searcher head at a smaller angle and irregularity of distribution oi intensity of UZK at this angle is small. This should always be remembered when defect is revealed when sounding in two opposite directions.

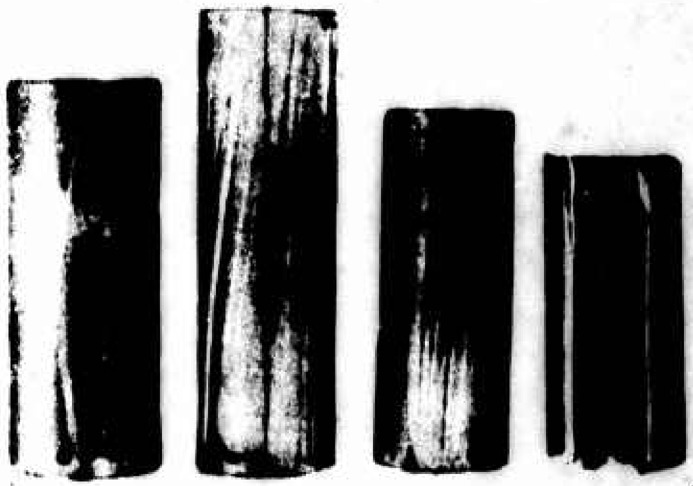

Fig. 256. Longitudinal and transverse cracks in nickel alloy rods, revealed during check with the aid of heads, sending in two directions (G. I. Misharin).

To ultrasonic check there is subjected not only large forgings, but also forged semifinished products of average dimensions, for instance rods with length <500 mm and diameter 35-40 mm, which are blanks for stamping gas turbine vanes. Metallurgical defects can be oriented both lengthwise and at an angle to axis of rod. Therefore, as practice has shown, the most reliable check is by echo-method in immersion variant at frequency 1.5-2.5 MHz with two beams (consecutively or simultaneously) directed one along the normal to lateral surface of rod, and the second at an acute angle to this normal in axial or lateral section. The second beam, being refracted at entrance to rod, is propagated in it obliquely, making it possible to reliably reveal oblique and transverse cracks; whereas the first beam reveals defects oriented longitudinally. After surface grinding the rod is dipped into bath with water and rotated. Searcher head, mounted in a special support, with the aid of hinged bracing, telescopic holder, and encompassing rods of bracket, while advancing along generatrix of rod and while scanning it along helix, can follow the possible pulsation of rod, ensuring preservation of established angle of introduction of beam at any point. In

Fig. 256 there are shown characteristic defects (longitudinal and transverse surface cracks) revealed in nickel alloy rods with such a check. It is necessary to emphasize that these defects are invisible to the naked eye and are not revealed with introduction of beam along the normal to lateral surface of rod (cracks are made visible on photographs with the aid of color method).

During check of large forgings, depending upon shape of forgings scanning is carried out by spiral or parallel lines. Automation in both cases is more easily carried out in immersion variant of the echo-method. During scanning of large flat surfaces with parallel lines, great productivity of check can be attained with the use of "broad range" searcher heads and especially multichannel systems, making it possible to check a wide band of surface and, consequently, considerable volume of metal in one pass. Creation of multichannel installations for automated check of large forgings will permit making this check very effective, reliable, and productive. With the contemporary state of semiconductor technology such installations can be sufficiently compact.

c. Check of Stampings

Check of stampings is considerably more complicated than forgings mainly because of complexity of shape of stampings. Orientation of metallurgical defects in stampings is also more complicated, as it is connected with direction of fibers of metal, to some degree following the outlines of the stamping. By macrostructure of the stamped blank it is possible to select the direction of introduction of UZK, ensuring their incidence on plane of defect along the normal (taking into account refraction on surface of stamping). Basic difficulty during check of stampings of complex shape involves necessity of selection of optimum angle of introduction of UZK at each point. During mass chack of uniform articles this can be carried out with the aid of a follow system, turning the searcher head to the needed angle and maintaining optimum distance between head and surface of introduction of UZK. However, until creation and wide introduction of such systems, check conducted manually by contact echo-method with sufficiently clean surface naturally cannot completely encompass the section of stamping to be checked. Certain parts of section can remain inaccessible for check in spite of the application of special searcher heads, intended for introduction of UZK at corresponding angles. It is necessary, however, to consider that the stamping

will subsequently be subjected to machining, at which part of the metal will be removed and the inaccessible sections can become more accessible. Therefore, it is expedient to conduct check of stampings at different stages of technological process – before mechanical and after mechanical and heat treatment; with this the volume of checkable metal will increase. Such a check, even if done manually, can be very effective, permitting revealing dangerous defects. Metallurgical defects are usually oriented along the fiber, therefore, with correct selection of direction of sounding it is possible to ensure more exact determination of dimensions of revealed defects as compared to forgings, where orientation of defects is less ordered. Inasmuch as metal in stamping is more deformed than in forging, and as a rule grain is finer, it is usually possible to carry out check at frequency 2.5 MHz if attenuation factor of UZK is small. Revealability factor of flat defects in stamping is lower than in forging, inasmuch as opening of defects is smaller and, as practice shows, does not exceed 0.1-0.25. During check of stampings of critical assignment sensitivity is established higher than during check of forgings, from which these stampings are manufactured.

Installations for automated check of stampings cannot be universal, calculated for check of stampings of any configuration. The problem of automated check of stampings represented by a solid of revolution is solved comparatively simply.

In Fig. 257 there is given diagram of [UKD-1] (УКД-1) immersion installation for automated check of stamped blanks of turbine disks.[1]

In this installation, intended for echo-method in immersion variant, the blank is placed on a revolving table in a bath with water. The searcher head scans the surface of blank along a spiral. Special mechanical follow-up system, transducer of which is a roller, is rolled along the surface of profiled pattern, controls the installation of searcher head 1, change of angle of introduction of UZK and distance from emitter to surface of blank. With this there are revealed volume metallurgical defects, and also flat ones, oriented perpendicular to axis of disk. However, the most dangerous defects for operation of disk are not these, revealed during check by conventional methods, but radial cracks and stratification, oriented in planes, passing through the axis of disk. Such

[1]Construction of installation, for the diagram offered by the author, is developed by B. A. Palkin, V. V. Musatov, E. O. Sakharov, V. R. Frolov, and B. G. Golodayev.

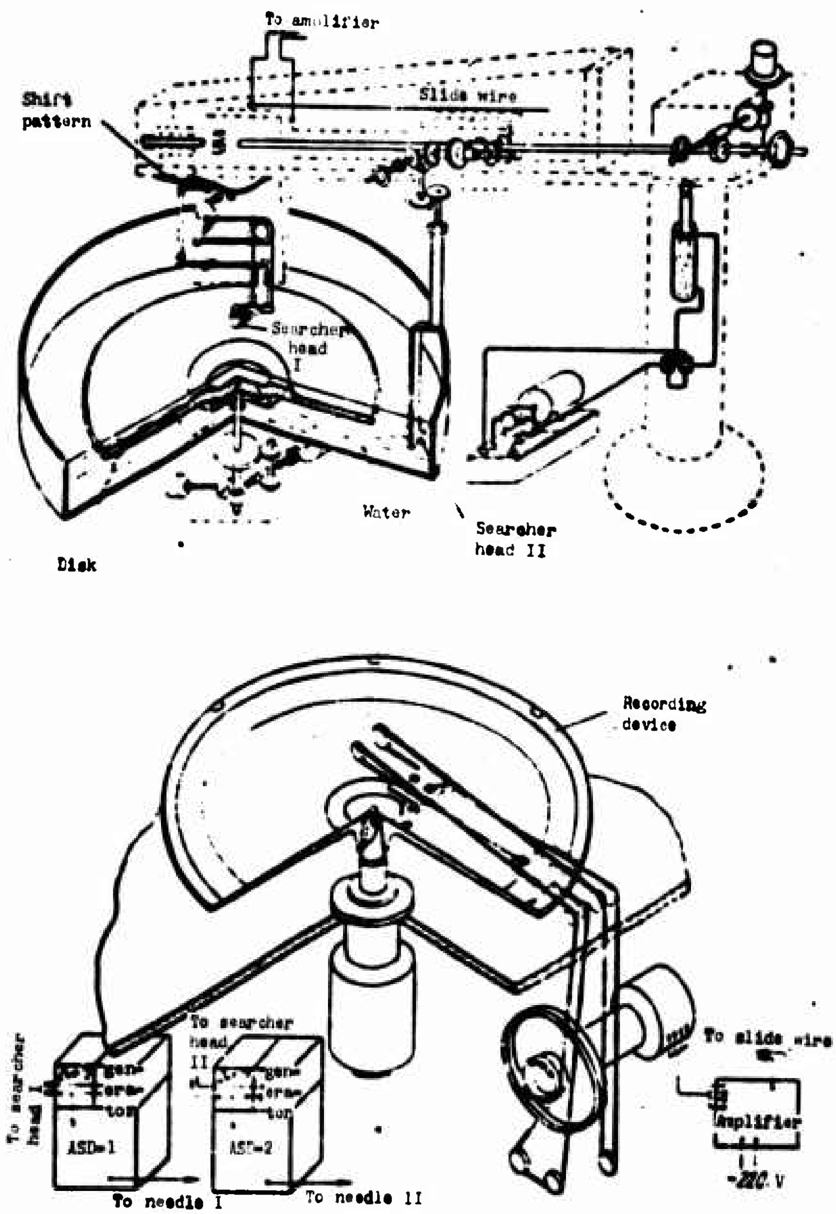

Fig. 257. Diagram of semiautomatic installation for check of stamped blanks of turbine disks.

cracks and stratification can be revealed if UZK are introduced through the axis of disk or parallel to the plane passing at a small distance from axis.

For this purpose in the installation there is provided second searcher head II, travelling in a vertical plane along the line parallel to generatrix of disk, coordinated with movement of head I. Both heads operate on two independent electrical channels with automatic signalling apparatuses of defects and with recording devices at output, working on "yes - no" system. Responses moving along both channels are recorded on electrothermal paper, lying on a special disk

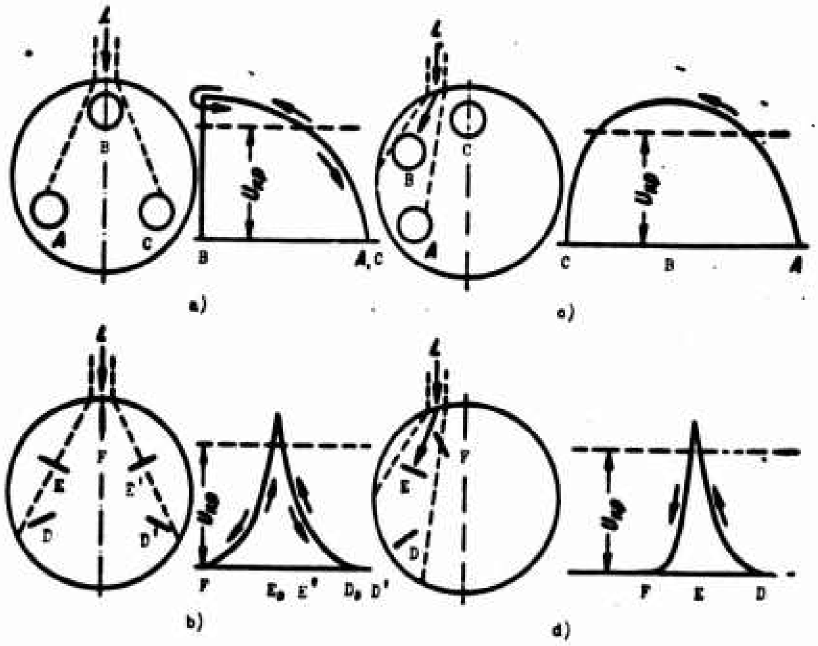

Fig. 258. Determination of character of defect by "wandering echo signal" a method during check of article having the shape of solid of revolution. Picture on the screen during deterction of volume defect — a) and radial crack — b); c, d) the same, with introduction of UZK not in a diametrical plane.

revolving synchronously with checked blank. Through the first channel head I gives a planned projection of blank with defects located in it. Through the second channel head II gives a sweep of lateral cylindrical surface of blank in polar coordinates, due to which images of contours of revealed defects are obtained somewhat distorted; however, coordinates of these defects can be determined quite accurately. Inasmuch as for indicators in UKD-1 installation there are also provided two electron-beam tubes, observation of echo signals on their screens permits obtaining additional information about the character of revealed defects. It is especially interesting to observe the echo signal entering through the second channel. Diagram of Fig. 258 shows that when sounding through the lateral cylindrical surface rotation of blank leads to continuous change of angle of incidence of UZK on surface of defect, to change of intensity of these UZK, and distance from point of introduction of UZK to defect. As a result of the combined action of these factors on the screen there is observed echo signal of changing amplitude travelling along sweep. Envelope of this echo signal has a different form, depending on character of revealed defect. For instance, in UZK are introduced into blank in diametrical plane and the revealed defect has

spherical shape (Fig. 258a), when this defect is in position A on the screen there will appear an echo signal of small amplitude (reflection of extreme rays of divergent beam of UZK from reflector, located at considerable distance). Further (in proportion to revolution of disk clockwise) the amplitude of echo signal will grow rapidly inasmuch as defect approaches axis of beam of UZK and the point of its introduction to blank (signal will be shifted on screen to the left). When defect appears on axis of beam of UZK and at minimum distance from point of introduction (position [B] (Б)), the amplitude of echo signal will reach maximum, after which it will start to decrease by approximately the same law (and echo signal will shift on the screen to the right). The picture observed on the screen during this is shown schematically in the right part of Fig. 258a.

If however, the defect is stratification oriented in radial plane, starting from position [D] (Г) (Fig. 258b) the amplitude of echo signal travelling to the left will increase to certain position [E] (Д), after which it will start to drop sharply and will become equal to zero in position [F] (E), in which stratification will be oriented along axis of beam. With further rotation of disk the same picture is repeated in the opposite direction, as is shown on diagram in lower part of Fig. 258b.

For increase of sensitivity during inspection of disks on the side of lateral cylindrical surface of blank it is expedient to displace the head on some distance from the diametrical plane, as is shown in Fig. 258c and d. Moreover, as a result of refraction of UZK on lateral surface of disk, shear oscillations will spread in it and amplitude of echo signal will increase, inasmuch as on the defect there will fall not extreme rays of beam of UZK, but central. With this the echo signal is shifted on the screen only to the left. Envelope of pulses observed on screen in this case will take a somewhat different shape, as is shown schematically in Fig. 258c and d during detection of spherical and flat defect respectively.

Inasmuch as recording device is controlled by automatic signalling apparatus of defects, working with the appearance of echo signal, amplitude of which exceeds a certain assigned level of $U_{кр}$ (shown by dotted line on diagrams of Fig. 258), the above considered peculiarities of detection of defects should be taken into account when deciphering obtained recordings. In particular, on the recording obtained by diagram of Fig. 258b each revealed stratification will be depicted

twice (with "asymmetric" diagram of introduction of UZK this will not be observed). Thus, automatic recording of responces of instrument does not always give a complete presentation about the revealed defect: observation of echo signals on screen of electron-beam tube can significantly supplement information.

In UKD-1 installation the follow-up system is mechanical, its basis – hinged parallelogram, controlled by roller, which is rolled along the surface of pattern having a special profile. A more flexible follow-up system is photoelectric, transducer of which is a photocell, sliding along the line traced on paper, and "held" on this line by a balanced circuit. Inasmuch as it is much simpler to trace and correct the shape of line than to prepare a special pattern by mechanical means, the photoelectric follow-up system should be recognized as very promising. Still more interesting is "reading" with the aid of ultrasonic transducers of system, for which patterns are not needed.

d. Check of Rods, Profiles, and Pipes

Check of rods, profiles, and pipes – semifinished products of average sections, usually produced by extrusion or rolling, is considerably simpler and more effective than check of stampings. This is explained by relative simplicity of shape of section of these semifinished products and also by higher degree of deformation of metal, ensuring production of fine-grained structure.[1]

Conditions of propagation of UZK in such metal are very favorable and permit obtaining sufficiently high sensitivity of checl. Surface cleanness of extruded semifinished products as a rule permits carrying out reliable introduction of UZK with use of immersion acoustic contact or contact through a thin layer of liquid. Special surface treatment is usually not required.

It is simplest of all to reveal extrusion shrinkage cavities in rods. During production of critical parts because of this defect it is necessary to cut part of the rod. Besides sometimes metal without defects is removed, since length of extrusion shrinkage cavity can turn out to be less than length of the cut part.

However, even the opposite case is possible: extent of extrusion shrinkage cavity can be greater than length of cut part of rod, in such a case the rod with

[1]In certain cases, however, in such semifinished products, for instance those manufactured from aluminum alloys, there is observed presence of coarse grain in subsurface zone, which leads to possibility of appearance of spurious signals and, consequently, worsens conditions of check.

remainder of extrusion shrinkage cavity can get into production.

Ultrasonic check, rather simply carried out by echo-method or shadow method in contact or immersion variants, at frequency 2.5 MHz permits determining the extent of extrusion shrinkage cavity and removing the defective part of rod at the length corresponding exactly to extent of defect. According to A. G. Gorokhov, during check of rods of 120-180 mm diameter from aluminum alloys it turned out that in only 10% the extent of extrusion shrinkage cavity coincided with length of cut part of rod, in 50% it was 100-300 mm less (i.e., part of rod without defects was removed), and in 40% of the rods – greater (i.e., part of the defect remained in the rod proceeding to further treatment).

Extrusion shrinkage cavity has the shape of a cone, therefore it is frequently revealed with introduction of UZK in the direction of any diameter – scanning can be conducted along generatrix; however, turning of rod increases the reliability of check and accuracy of determination of size of extrusion shrinkage cavity. During check of rods with the presence of internal cracks, oriented along diameter, in accordance with considerations presented when examining the diagram of Fig. 224, it is necessary to continuously revolve the rod and to carry out scanning along a helix – otherwise it is possible to tolerate the crack oriented in the direction of beam.

Check of profiles is somewhat more complicated than check of rods. As compared to a round rod the shape section of profiles is more complicated, and often asymmetric, however, inasmuch as a considerable part of the lateral surface of profile comprises planes, it is considerably simpler to check profiles than stampings. In profiles it is usually required to reveal internal cracks and stratification, extrusion shrinkage cavities, "end" surface cracks, and slag inclusions. Besides, in closed type profiles, having closed impression and produced from aluminum alloys by method of extrusion with a tongue-type die, it is necessary in the presence of stratifications to check the longitudinal seam formed by means of pressure welding of two halves of extruded profile at the moment of its passage through the die.

Check in the presence of internal cracks (Fig. 259) and stratifications can be carried out by the echo-method in contact or immersion variants. Surface "end" cracks (Fig. 260) are easily revealed by the echo-method in contact variant with the aid of special searcher heads, radiating surface waves. Closed type

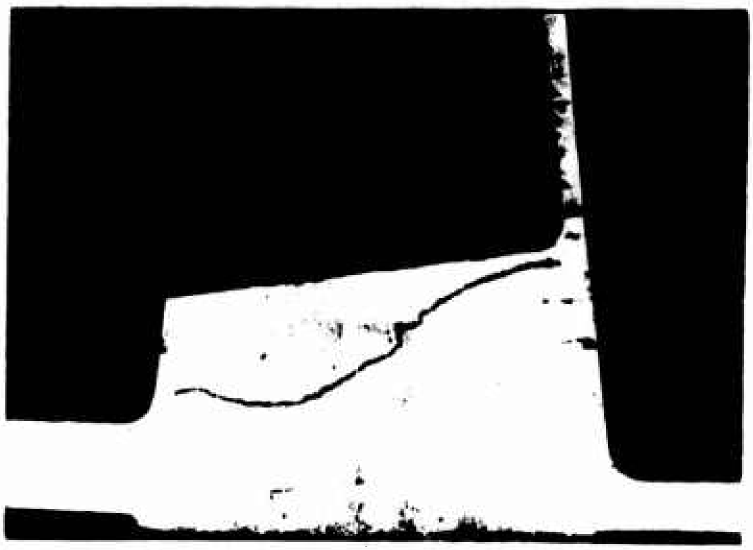

Fig. 259. Internal crack in extruded aluminum alloy profile (Ya. A. Rublev).

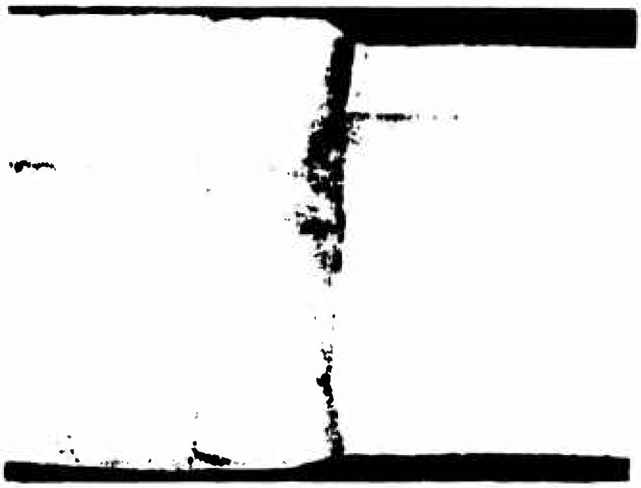

Fig. 260. "End" cracks on surface of aluminum alloy profile (A. P. Saltykov).

profiles, usually having walls of small thickness, can be checked either by mirror-shadow method in immersion variant by echo-method in contact or immersion variants with use of refracted shear oscillations. In the first case (Fig. 261), inasmuch as water also fills the internal cavity, on the screen of echo-flaw detector there will be seen an echo signal reflected from internal surface of lower shelf of profile. With the presence of deep cutoff in the instrument circuit, making it possible to observe this signal without clipping, it is possible by decrease of its amplitude to indicate the presence of defect in the upper shelf of profile. In the

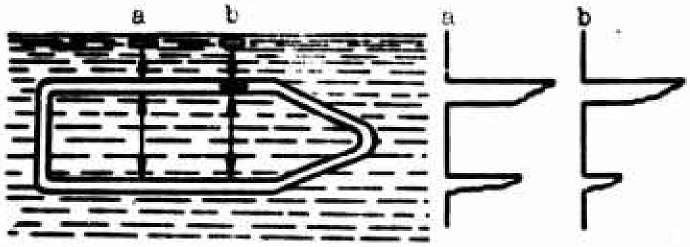

Fig. 261. Diagram of check of closed type profile by mirror-shadow method in immersion variant.

second case longitudinal UZK, observed oblique to the surface of profile, are transformed during refraction into shear. spreading in upper shelf (Fig. 262). Defects located on external or internal surfaces and also inside the shelf, are easily revealed in a wide range of frequencies. However, it is difficult to determine dimensions of revealed defects in a number of casses. Thus, if metallurgical defect (slag or nonmetallic inclusion) has a shape close to spherical, amplitude of echo signal is determined mainly by dimensions of defect and scarcely depends on direction of beam falling on it. However, if defect is extended in the direction of extrusion, as is shown in Fig. 262, amplitude of echo signal is determined by sum of areas of sections of surface oriented perpendicular to incident ray, and not the entire surface of defect. It is impossible to determine revealability factor.

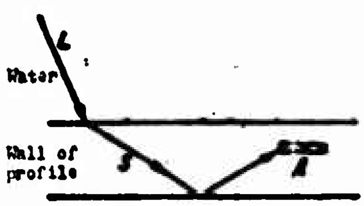

Fig. 262. Diagram of check of profile by echo-method with use of refracted shear oscillations S, forming as a result of transformation from longitudinal L.

It is necessary to emphasize that certain profiles from aluminum alloys, utilized in aviation technology, operate in so complex loading conditions that the smallest defects sharply lower strength characteristics of the construction. Therefore, during check of such profiles the flaw detector is tuned to very high sensitivity, making it possible to reveal, for instance, slag inclusions with size 0.5 mm and higher.

For increase of reliability and objectivity it is expedient to conduct such a check on a specialized installation with mechanized and automated process of check, and also recording of results. The author, together with B. G. Golodayev, M. P. Ural'skiy, A. I. Murashov, A. I. Litvintsev, V. D. Zhukov, and V. A. Smirnov developed two variants of installations for check of extruded aluminum alloy profiles in shop conditions. The installation made according to the first variant operates at frequency 5 MHz. Powerful pulses of

longitudinal UZK are introduced by slanted searcher head at incidence angle $\alpha = 20$ degrees, exciting shear UZK in shelf of profile, spreading at refraction angle $\beta = 49$ degrees. Generator and searcher head are mounted on a carriage, which can be moved over a special guide along the bath at a rate up to 0.6 m/s. In outermost positions the movement of carriage is automatically reversed, and the searcher head is shifted simultaneously one step in transverse direction. Next to the bath on metallic tape there is fastened electrothermal paper, on which the recording device traces lines in accordance with motion of searcher head, thus recording responces of automatic signalling apparatus of defects by "yes - no" system. During operation of automatic signalling apparatus of defects a special device marks the section in which defect is revealed on the surface of controlled profile with paint. Thus, the profile checked on two sides is removed from bath and subjected to a secondary check by contact echo-method in sections marked with paint. With this we more thoroughly estimate dimensions of defect and determine depth of its occurrence. For determination of coordinates it is necessary to know the spacing of zigzag-like propagation of shear UZK in the wall of profile and the thickness of this wall. By these data it is very simple to construct graphics for determination of depth of occurrence of the revealed defect.

Experience of check of profiles on such an installation showed that very high sensitivity is ensured, making it possible to reveal the most insignificant metallurgical defects. However, productivity of check is completely insufficient for industrial conditions, since the speed of longitudinal shift of the heavy carriage is limited by the necessity of its frequent reversing. Increase of productivity of installation can be accomplished, for instance, by means of simultaneous check of several profiles placed into bath, as is shown in Fig. 263, and sounded on two sides with the aid of a corresponding number of equipment channels. It is possible to install profiles preliminarily outside the bath in special housings, after which all profiles are loaded simultaneously into bath with the aid of a crane.

Such a system is used in the installation completed by M. P. Ural'skiy and A. I. Murashov according to the second variant (Fig. 264). In it, besides, there is applied the original circuit of transverse scanning. By this diagram

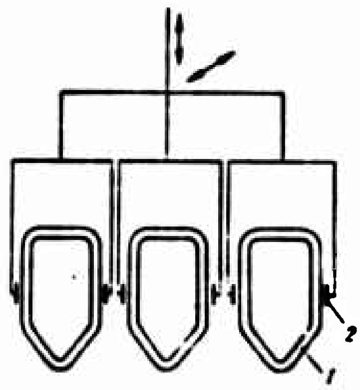

Fig. 263. Diagram of simultaneous check of several profiles: 1 – profiles; 2 – searchers.

Fig. 265. "Broad range" searcher head for accelerated check of large articles.

longitudinal movement of carriage is comparitively slow, and searcher heads perform rapid up and down movement within limits of entire width of profile with the aid of a special roller with a two-way spiral groove cut in it. Reversing of the heavy carriage is eliminated with this and scanning can be considerably accelerated. Results of check are recorded on chart paper with mark of section in which the defect is revealed. For exact determination of coordinates of defect there is conducted a repeated "manual" check on marked sections.

In the sense of increase of productivity the use of "broad range" searcher heads can also give a very considerable effect. Such a head, general view of which is shown in Fig. 265, gives a field about 100 mm wide with oscillations of intensity of UZK along width not higher than 15%. During check with the aid of broad range head in one pass there is checked an area, for sounding of which with the aid of a standard head (with piezoelement of 15 mm diameter) there is required approximately 25 passes. With this, of course, there can be marked only the section in which the defect is revealed, exact coordinates of defect should be determined only with repeated limit check by contact echo-method in marked sections. Recording on electrothermal paper in these conditions loses its value.

Check of pipes in the last few years, especially in connection with development of atomic power engineering, became a very urgent problem, attracting the attention of many researchers. In various branches of industry there are applied pipes from different materials, having the most diverse diameters and wall thicknesses. Besides, in special constructions there are used pipes with variable wall thickness and also with variable profile. It is therefore necessary to check

pipes of critical assignment for the presence of various kinds of defects inside the wall, and also on internal and external surface. It is also required to check wall thickness of pipes (especially if this thickness is variable). It is necessary to carry out this check in the process of production and operation of pipes. Wall thickness of pipe is usually measured by the resonance method. For thickness over 5-8 mm there can also be applied the method of multiple reflections with usage of echo-flaw detector; however, accuracy of measurement is considerably less than in resonance method. Resonance method gives completely sufficient accuracy for practice, but its productivity in contact variant is small. Therefore, the resonance method in immersion variant has indisputable advantage. Besides high productivity and ease of automation, it permits, while using ultrasound focusing, carrying out check of pipes with very small diameter (up to 3 mm) with a thin (up to 0.2 mm) wall. Responces of instrument are obtained very clear, since interferences from shift oscillations, observed with contact variant, are absent. There is also facilitated check of wall thickness on the side of concave surface, which permits solving such problems as, for example, measurement of wall thickness of hollow blade of gas turbine both on the convex "back" side and on the concave side.

Method of measurement of thicknesses with the aid of normal waves, offered by Frederick and Worlton [249], permits obtaining very high (~0.1-0.2% of the measured thickness) accuracy during check of pipes with small wall thickness. Inasmuch as it is also carried out in immersion variant, all the advantages connected with the use of contact of this type are kept.

Method is based on the presence of simple coupling between frequency of oscillations introduced into article, angle of incidence of these oscillations, and thickness of checked article. Emitter sends into article either continuous oscillations, modulated by frequency (as in resonance thickness gauge) or, which is more convenient, narrow pulses with space frequency changing from pulse to pulse. At given incidence angle and given thickness the article, acting as a unique filter, passing oscillations of specific frequency. Measurement of this frequency by a receiving device permits determining thickness with high accuracy (Fig. 266). It is necessary to consider that both surfaces of pipe, in the wall of which during excitation of normal waves the energy of UZK spreads, as in a waveguide, radiate this energy into environment, which leads to drop of

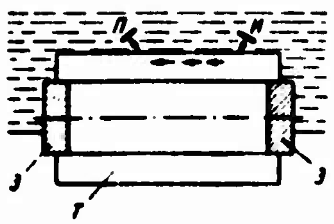

Fig. 266. Diagram of measuring the wall thickness of pipe by immersion method with the aid of normal waves [249]: И – emitter; П – receiver; T – pipe; 3 – end caps.

sensitivity. It is natural that quantity of radiated energy and drop of sensitivity depends on wave impedance of environment, for air it will be considerably less than for water. Sensitivity can be increased if contact is accomplished in such a manner that possibly a smaller surface area of pipe would be moistened by water; water should not get inside the pipe, and UZK should be introduced at the "point" with the aid of special heads with jet contact. By exciting normal waves in wall of pipe by pulsing with different space frequency, it is possible to successfully check these pipes for the presence of various kinds of defects on external and internal surface, and also in wall thickness of pipe. Space frequency can be changed periodically in small limits (this permits compensating the effect of change of wall thickness of pipe within tolerance limits) or by a prescribed law determined in advance (this gives possibility to check quality of pipes with wall of variable thickness). Of course it is possible to carry out such a check with pipes of not only round, but also any other section (Fig. 267), inasmuch as it is not necessary to rotate the pipe.

Fig. 267. Diagram of check of pipes by echo-method with use of normal waves and a special head with jet contact: И – head; T – pipe; Д – defect.

Check with use of normal waves is very effective for pipes of small and average diameters with small wall thickness. With increase of diameter and wall thickness of pipe there is increased effectiveness of check with use of shear UZK (Fig. 268). It is possible to conduct check either in contact or in immersion variant. In first case, analogous to that which was already noted during analysis of operation of refracting searcher head, there appears necessity of check of reliability of acoustic contact. This problem is very simple to solve by using two heads, connected in parallels and oriented in opposition to each other, as is shown in Fig. 231.

With increase of wall thickness of pipe at its constant external diameter the angle of incidence of beam on internal surface of pipe becomes considerably larger than angle of introduction through external, as a result of which sensitivity of detection of defects of stratification type, oriented in section of

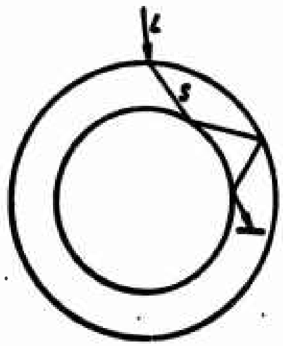

Fig. 268. Diagram of check of pipes by echo-method in immersion variant with the use of shear UZK.

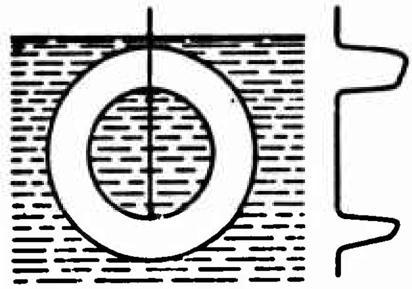

Fig. 269. Diagram of check of pipes by mirror-shadow method in immersion variant.

pipe along an arc, drops noticeably. Therefore, angle of introduction should be selected depending upon external diameter of pipe and its wall thickness, decreasing it in proportion to increase of this thickness. With wall thickness exceeding ~0.2 of magnitude of external diameter, there becomes expedient the application of longitudinal UZK introduced along radius of pipe, analogous to that during check of rotors of turbogenerators.

Check of thin-walled pipes for the presence of stratifications can also be carried out by mirror-shadow method (Fig. 269). In this case the presence of stratification can be indicated by decrease of amplitude of echo signal reflected from a point on the internal surface, lying on the opposite end of diameter of pipe with respect to point of introduction of UZK.

For check of quality of pipes with use of shear and longitudinal waves rotation of pipe is necessary; therefore, equipment should be more complex than during use of normal waves – from this point of view the advantage of methods based on the use of waveguide effect is indisputable. Moreover the sensitivity of these methods is very high. However, in certain cases even such high sensitivity can be insufficient for detection of dangerous defects. The point is that reflection of normal waves occurs as a result of change of section of waveguide. This change is determined mainly by area of projection of defect on a plane perpendicular to direction of wave propagation. In reference to stratification in wall of pipe – this is area bh (see Fig. 270). Extent of stratification l in the direction of wave propagation does not practically affect

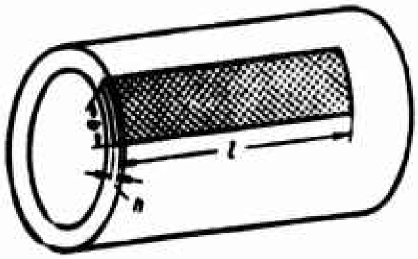

Fig. 270. Conditions of detection of stratifications in thin-walled pipes.

reflection of UZK. Therefore, dangerous defect – stratification, for which extent (l) is great, and opening (h) is small, can be undetected. However, with the same sensitivity there will be revealed transverse surface scratches, often not presenting such danger as stratification.

From this a conclusion can be made concerning expediency of check of thin-walled pipes (of round section, inasmuch as it is necessary to revolve the pipe) for stratifications by mirror-shadow method with use of longitudinal UZK of stepped up frequency (to several tens of MHz). At such frequencies there will be revealed stratifications with the most insignificant magnitude of opening.

During check of telescopic pipes, when introduction of UZK on the side of external surface is hampered, if internal diameter of pipe permits it is possible to introduce UZK on the side of internal surface. For thick-walled pipes it is expedient to use shear UZK with frequency 2-4 MHz, exciting them in wall of pipe by means of transformation from longitudinal, radiated by piezoelectric converter to the segment from organic glass.

If it is necessary to reveal defects located near the internal surface or coming out on this surface in pipes with internal diameter >30-40 mm and with wall thickness >3-4 mm, by introducing a special searcher head on a long holder into pipe it is possible to send surface UZK along internal surface in the direction of generatrix. With this there can be ensured very high sensitivity, permitting revealing the smallest surface defects. However, with such high sensitivity there can also be observed false echo signals, for instance as a result of reflection of UZK from characteristic trace on the surface having the shape of a helix and formed during manufacture of pipes (usually steel) on "Rockrite" mills, distinguished by unigue kinematic diagram of rolling. False echo signals can also appear with other diagrams of check of pipes, and in order to correctly decipher the observed picture there is needed sufficient experience and reliably working equipment. Construction of installations for check of pipes is therefore an important problem, solved by many researchers [152-154, 206, 250, 251]. A successful construction – [IDTs-3M] (ИДЦ-3М) installation is developed by TsNIITMASh and is released by the "Elektrotochpribor" (Fig. 271). It is

also possible to consider the earlier mentioned installation, developed in FRG and the United States, as successful.

Basic data of IDTs-3M installation:

Diameter of pipe that can be checked, mm .	6-60
Wall thickness, mm	0.2-2
Length of pipe, m	<3
Frequency of UZK, MHz	2.5
Minimum dimensions of revealed defects (length of stratification), mm	3-5
Depth of cracks, mm	0.05
Speed of rotation of pipe, r/min	300

Another domestic installation for check of pipes in plant conditions, described by A. G. Nikolayenko and Ya. F. Anikeyev [154], permits at frequency 2.5 MHz the revealing of insignificant stratifications (with extent from 0.3 mm with opening in several microns) in bimetal pipes of 9.7, 12, and 20 mm diameter with wall thickness 0.7, 0.8, and 0.2 mm respectively. Pardus [250] indicates the possibility of check of pipe with 2 mm diameter and wall thickness 0.25 mm with the aid of UZK of frequency 1 MHz.

e. Check of Rolled Plates

Check of rolled plates is a problem analogous to check of forgings, but is probably less difficult inasmuch as the plate has a simpler shape and smooth surface. During check of plates the basic question requiring a special solution is productivity of check. The most correct should be considered application of echo-method or mirror-shadow method (and both – in immersion variant). Considerable surface area of plate makes line scanning inexpedient: There is necessary development of multichannel systems, permitting check of a wide zone simultaneously. Depending upon thickness of plate, material from which the plate is manufactured, and also upon the nature of revealed defect, the optimum frequency of check can be changed within limits of ~1.5-2.5 MHz. However, during check of aluminum alloy plates in certain cases the use of UZK of such frequency can be little effective. The point is that such plates are often subjected to "chemical milling" for the purpose of obtaining a ribbed panel. Oxide films, oriented so that they will intersect the thin ribs of panel,

significantly weaken its strength, and are therefore impermissible. Meanwhile, as already was noted, coefficient of reflectivity of UZK from layer of aluminum oxide in aluminum is extremely low (at frequency 2.5 MHz it is equal to ~0.01, see curves of Fig. 85), therefore it is practically impossible to reveal it. In metal subjected to great deformation, it is possible to reveal oxide films by deformation stratifications accompanying them. However, inasmuch as opening of these stratifications can be insignificant, it can be that it is expedient to considerably increase frequency of UZK. Of course maximum thickness of plate, check of which is possible at such frequencies, is sharply decreased with this.

If steel plates or plate from other metals are subjected to check for presence of stratifications, having an air gap, such a problem is solved considerably simpler at UZK of average frequencies and even by usual shadow method, inasmuch as revealability factor of stratifications is rather high and in certain cases is close to one. Use of searcher heads with jet contact developed for this purpose by Krautkremer (Fig. 272, 273), permits making the check sufficiently reliable and with manual scanning.

f. Check of Sheets, Strips, and Wire

Check of sheets. Insignificant thickness of sheet permits using normal waves along with longitudinal UZK, applied during check of plates. Therefore, check of sheets can be carried out by several methods. Thus, resonance method in contact and immersion variants can be used with success for check of thickness of sheet at any point, including thickness so far from edge of sheet that measurement by micrometer is impossible. With this rough stratifications in sheet can also be revealed.

Shadow and especially mirror-shadow methods in contact and immersion variants at frequencies about 1-4 MHz can be very effectively applied for detection of thin stratifications, and with increase of frequency to several tens of MHz — for detection of oxide films. Application of echo-method for this purpose for a long time was considered impossible for sheets of less than 10-15 mm thickness inasmuch as the presence of a dead band does not permit resolving echo signals from stratifications located at a depth less than 5-7 mm. However, as Krautkremer has shown, by decrease of number and amplitude of echo signals from opposite surface of sheet and by reduction of distance between them, it is

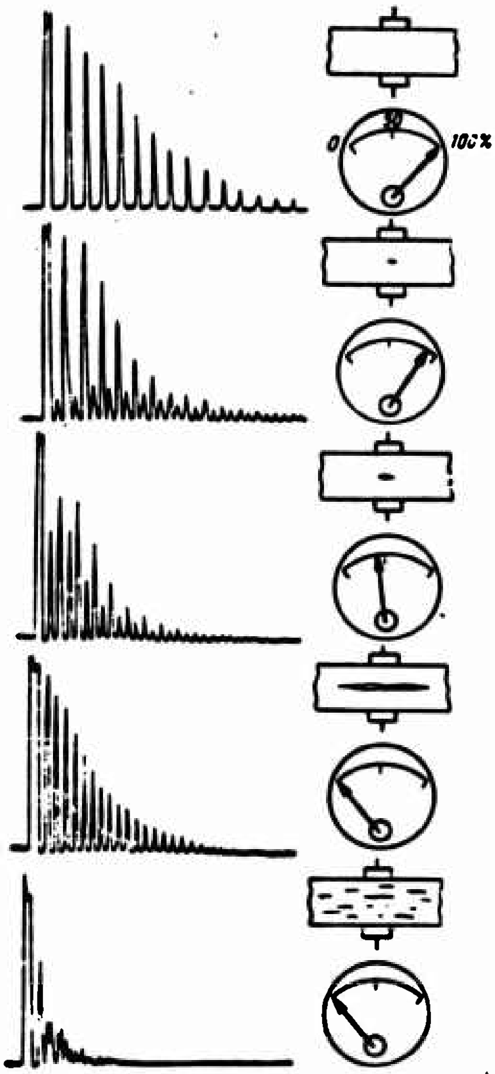

Fig. 274. Check of sheets (thickness of sheet 15 mm) by echo-method. On the right – corresponding responces of instrument during check by shadow method.

possible to reveal stratifications in sheet and at smaller thickness. In Fig. 274 there are given photographs from screen of echo-flaw detector during check of sheet of 15 mm thickness, echo signals from stratifications located at a depth of 7-8 mm are still allowed and by increase of their amplitude and decrease of amplitude and quantity of bottom echo signals it is possible to indicate the presence of stratification and its dimensions. However, if echo signals from stratification are not allowed, merely decrease of number and amplitude of bottom reflections permits indicating the presence of stratifications in sheets with minimum thickness about 2 mm (at frequency ~5 MHz).

Sheets with several millimeters thickness are more expediently checked by applying normal waves. Conditions of check are analogous to those examined for pipes, with the difference that considerable width of sheets sometimes forces conducting check with bands of definite width. The sheet be oriented in a horizontal plane, and introduction of UZK – carried out on the side of lower surface in a direction perpendicular to direction of rolling. In such a way it is possible to carry out check, for instance, in the process of real rolling. If, however, comparatively small sheets are subjected to check (length up to 2-3 m and width up to 600-800 mm), it is possible to orient the sheet in vertical plane, having dipped it 100-150 mm in water and introducing UZK with the aid of a head, located in water at lower edge of sheet.

In this case the installation can be more compact and will occupy a smaller area.

During check of sheets by normal waves the direction of sounding is usually perpendicular to direction of rolling. This is expedient because defects, which

had approximately identical length and width in plate, in the sheet are extended in the direction of rolling many times, and of course, it is easier to detect then when sounding in transverse direction.

Methods and equipment for check of sheets in industrial conditions, based on use of longitudinal or normal waves, with automation of check and recording of results were successfully developed mainly in FRG [252-256].

Check of thin strip and wire can be carried out very successfully with use of normal waves. During this the strip of wire is rewound from one drum to another, and check is produced on a section with ~200 mm length, for which with the aid of a special head with jet contact, moistening only an insignificant section of lower surface of strip or wire, there are exicted normal waves, giving a clear echo signal from surface and internal cracks, stratifications, and other defects.

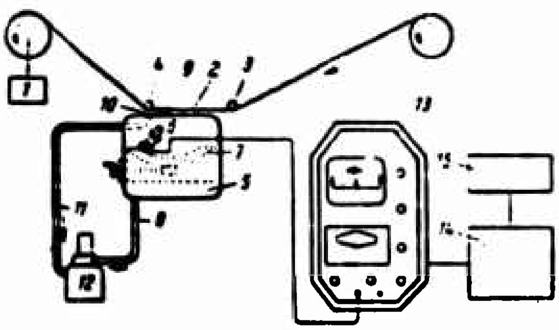

Fig. 275. Diagram of check of wire according to Lehfeldt with application of normal waves: 1 – drive; 2 – section to be checked; 3, 4 – riders; 5 – housing of head; 6 – head; 7 – gear segment; 8 – feed tube; 9 – flow contact; 10 – water overflow; 11 – discharge tube; 12 – pump; 13 – echo-flaw detector; 14 – automatic signalling apparatus; 15 – recorder.

Diagram of installation of Lehfeldt firm for check of strip and wire [257] is shown in Fig. 275. Installation permits carrying out check at a rate of 3-5 m/s, during which sensitivity of equipment ensures detection of longitudinal and transverse cracks 0.01 mm deep and slag inclusions of 3-5 μm diameter in wire of 0.2 mm diameter. In principle the installation can also carry out check of larger diameter wire.

It is necessary to note that during control with use of normal waves, by responses of instrument it is impossible to distinguish the external defect from deep: instrument indicates only the section in which defect is located. During check of article of large thickness it is possible, while changing angle of incidence of UZK, to excite only surface waves, and to thus distinguish surface and deep defects.

g. Check of Multilayer Articles

Check of multilayer articles has its peculiarities and can be carried out by various methods. Multilayer articles can include bimetal rods, sheets, and

pipes, in which cohesion between separate layers of metal appears in the process of treatment by pressure, two- and three-ply brakes disks, in which cohesion is ensured in the process of diffusion sintering, metallic shells, covered with layers of nonmetallic heat-shielding coverings glued to them, and others.

During selection of method of check it is necessary to consider material of each layer of article, method of connection of these layers into one integer, character and dimensions of defects subject to detection. Multilayer sheets and pipes in many cases can be checked with the aid of normal waves.

Brake disks are subjected to check by shadow (or mirror-shadow) method, permitting revealing zones in which there is no cohesion between cermet friction element and steel base (light spots in Fig. 276).

For check of glued articles the best results are given by acoustic methods — impedance and method of free oscillations, and from ultrasonic — echo-method in variant at which there is recorded change of phase of oscillations (frequency — several tens of kilocycles), reflected from opposite surface of article in healthy and in defective sections, and velocimetric method developed by Yu. V. Lange, based on measurement of propagation rate of normal waves in defective section.

h. Check of Weld Joints

Ultrasonic methods are widely used for check of weld joints. In essence, this special region of ultrasonic flaw detection, solving the problem of check of quality of welded seams of different thickness (from several millimeters to half a meter), carried out by various methods. Methods of check of weld joints are described in a great number of special works [258-284];[1] therefore, here they are handled very briefly.

Shape of weld joints, orientation of basic defects of weld, presence of reinforcing run make check by shadow or echo-method with aid of normal searcher head, radiating longitudinal UZK, possible only in separate rare cases. As a rule check is produced by echo-method with shear UZK, radiated by refracting heads. Diagrams of check of certain welded seams are shown in Fig. 277. With such check there are revealed metallurgical defects of seam — slag inclusions, blowholes,

[1]See also A. K. Gurvich. Author's certificate No. 104659, USSR, 1956, H. E. van Valkenburg, E. G. Cook, DBP, 1057356, 1959.

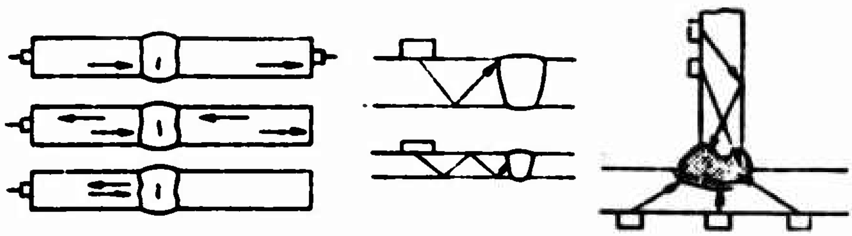

Fig. 277. Check of weld joints: a) with longitudinal UZK by shadow echo-method; b) with refracted beam (shear UZK) by echo-method; c) tee connection by echo-method.

gas pores, and also cracks and spilly places. Optimum frequency of UZK depends on welded material and on thickness of welded seam. In most cases check is conducted at frequency 2.5 MHz. However, with considerable thickness of seam, and especially during check of seam in steels of austenitic class the frequency should be lowered to 1.5-0.5 MHz, which is connected with considerable damping of UZK in zone of thermal effect, 2-3 times exceeding damping in base metal.

For check of butt joints we usually use refracting searcher heads with a housing of organic glass, with different angles of incidence of longitudinal of UZK, intended for propagation of shear UZK in metal at angles from 38 to 80 degrees.

This angle should be selected depending upon thickness of seam and bevel angle of edges, since during check shear UZK should be directed as perpendicular as possible to edge, in order to ensure optimum conditions for detection of the most dangerous defects (spilly place along edge and cracks). Along with straight beam usually for this purpose it is convenient to use a beam, singly or multiply reflected from opposite wall of weld joint. In order to check the seam along entire height, it is necessary to shift the shearcher head zigzag-like within limits of band of definite width, parallel to seam (Fig. 278a).

It is possible instead of this to apply "scanning beam" method, carried out according to diagram of Fig. 278b with rectilinear advance of head parallel to seam, or by diagram of Fig. 278c with a head containing mosaic of piezoelements [284], shifted in definite sequence.

Instead of scanning beam it is possible to carry out check by method of "rocking" beam with the aid of a special head, travelling parallel to seam, in which piezoelement continuously accomplishes reciprocal-rotatory motion within limits of a certain angle (Fig. 278d).

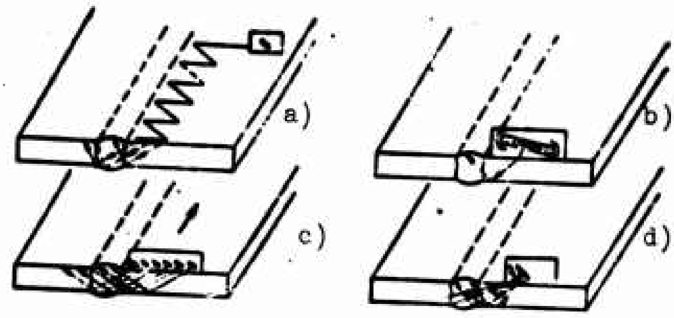

Fig. 278. Diagrams of check of weld joint: a) zigzag-like scanning; b, c) "scanning beam" method; d) "rocking beam" method.

One of the peculiarities of check of weld joint is the absence of bottom signal; therefore, it is especially important to ensure reliable acoustic contact.

Type of defect in separate cases can be based on preliminary statistical analysis of results of check of given type of seam, established according to type echo signal reflected from it. Thus, a spilly place gives a clear single peak, inasmuch as reflection occurs from a comparatively flat furface (Fig. 279a), a winding crack is usually depicted as is shown in Fig. 279b, group of cracks — in the form of several peaks of small amplitude (Fig. 279c), porosity gives a great number of peaks on wide section of scanning (Fig. 279d).

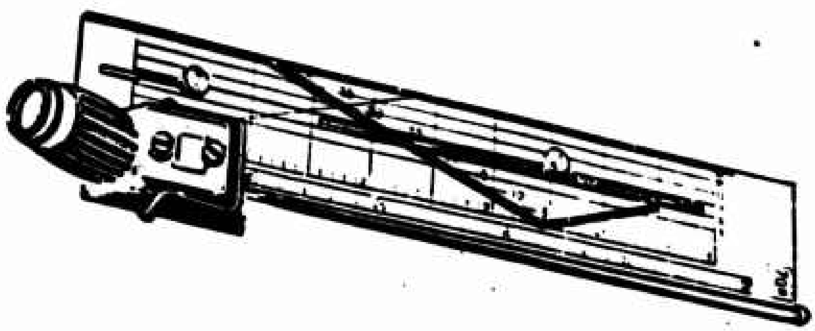

Fig. 280. Calculation plotting board for determination of coordinates of defect revealed during check of weld joint (Krautkremer).

For determination of coordinates of defects revealed during ultrasonic check there are developed special calculation plottings boards, making it possible to rapidly solve this problem for weld joints of different thickness and various angles of refraction (Fig. 280). With application of specialized flaw detectors of type [UZK-NIIM-5] (УЗК-НИИМ-5) for check of welded seams, determination of coordinates is produced directly by instrument scale.

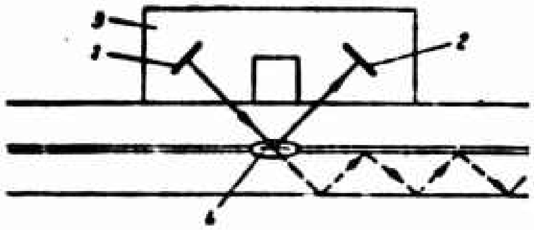

Fig. 281. Diagram of check of quality of spot welding: 1 – radiating piezoelement; 2 – receiving piezoelement; 3 – housing of head; 4 – spilly place in weld point.

It is quite difficult to estimate dimensions of defects revealed in weld joint. Check of spot and roll welding is developed least of all. Weld joints of this type are distinguished by the fact that they do not have reinforcing run; however, even in this case check is possible only with the aid of refracting searcher heads if they are located at a certain distance from welded seam. This is connected with the presence of a characteristic dent above the seam – traces from contacts of welding machine. Diagram of check of weld point is shown in Fig. 281. With the presence of defect in weld point the reflected beam gets on receiving piezoelement of dual searcher head. If there are no defects in weld point, the beam sent by radiating plate passes into lower sheet and is propagated in it, signal does not proceed to receiving plate. It is necessary to note that during ultrasonic check of these weld joints, as a rule, it is not possible to reveal a very dangerous defect – so-called "adhesion" – special type of spilly place at which both surfaces of combinable parts are tightly compressed, there is no noticeable gap between them, but at the same time there is also no diffusion.

It is obviously that it is possible to reveal "adhesion" at stepped up frequencies; however, it is difficult to use UZK of such frequencies for check of weld joints.

i. Check of Articles in Operation

Ultrasonic check of articles in operation is very effective. In a number of cases this is possible to do without dismantling (and sometimes even without stopping) of aggregate.

As example it is possible to cite check of crankshafts for presence of internal cracks, usually appearing in transitions from side to neck and oriented at a ~45 degree angle to axis of shaft.

Such cracks can be easily revealed by echo-method at frequency 2.5 MHz with the aid of refracting heads, radiating shear UZK, as is shown in Fig. 282a and b.

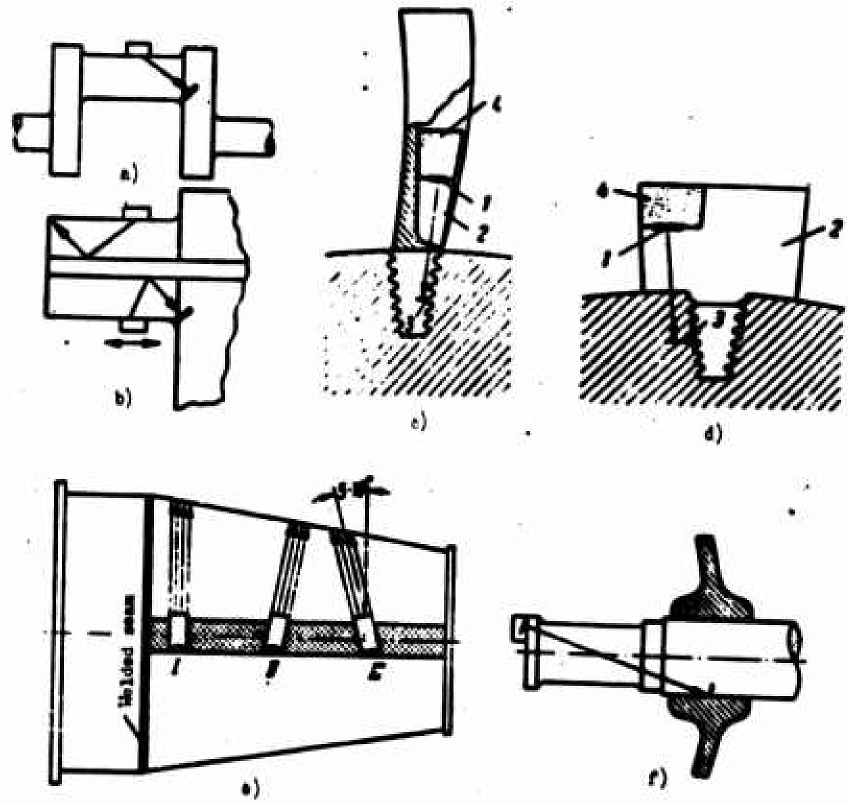

Fig. 282. Diagram of detection of cracks: a and b) in crankshaft (without internal channel and with channel, respectively); c) in joint of turbine blade, mounted in disk; d) in slot of herringbone bracing of turbine disk; e) in housing of combustion chamber; f) in access part of axle of railroad car [288].

For guarantee of reliability of gas-turbine engines there is necessary check of compressor and turbine blades for presence of cracks, developing mainly on edges. Such check is successfully carried out with use of surface UZK at frequency 1.5-2.5 MHz with the aid of a specialized echo-flaw detector, for instance [UZDL-61] (УЗДЛ-61) [285].

With the presence of sufficiently convenient access to compressor and last stage of turbine, and to corresponding attachments for introduction, installation, and remote control of operation of searcher head, check of blades can be carried out without dismantling the motor. There is also possible check of blades for presence of cracks in joint (in grooves of herringbone bracing), also without dismantling of turbine. Such type of check is illustrated in Fig. 282c, where 1 is piezoelement, 2 – housing of head from material analogous to material of disk with respect to rate of propagation of UZK. Further on this figure: 3 –

crack, 4 — damper.

Cracks on edges and in blade joint may also be revealed by color method; however, complete disassembling of turbine is absolutely necessary for this. For detection of cracks in grooves of herringbone bracing of turbine disk by ultrasonic method it is necessary to dismantle the turbine and "split" the disk. Check can be conducted by echo-method with the aid of a special head, directing shear UZK, as is shown in Fig. 282d.

In combustion chambers of gas-turbine engines it is possible to reveal cracks of thermal fatigue by echo-method with use of normal waves of UZK with frequency 2.5 MHz according to diagram shown in Fig. 282d (I, II, III — consecutive positions of searcher head).

Ultrasonic methods are widely used for check of railroad construction in conditions of operation. Thus, axes of wheel couples are subjected to check for presence of fatigue cracks in access part, inaccessible to inspection [286]. Check is conducted by echo-method at frequency 2.5-1.5 MHz. Longitudinal UZK are introduced from cracks as is shown on diagram of Fig. 282f.

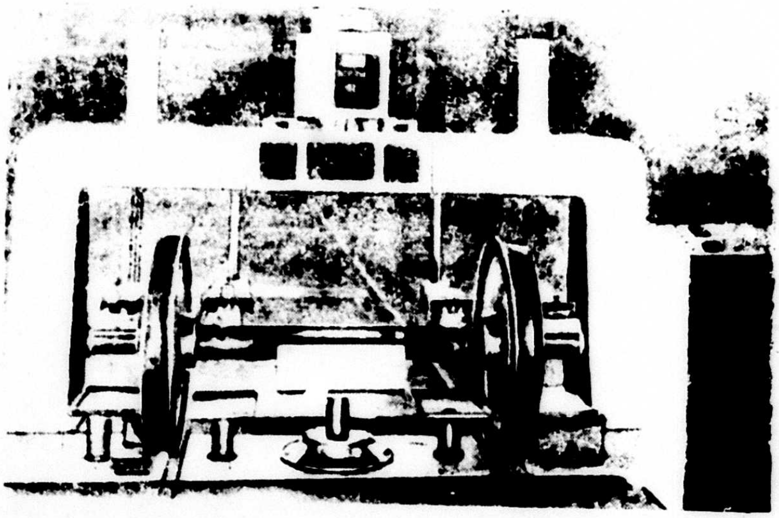

Fig. 283. Semiautomatic installation for check of wheel spacing of railroad cars [94].

For rapid check of axle in FRG there are developed special automated installations (Fig. 283). Simultaneously with this in the access part of axle there can be carried out check of qualities of press fit of hob [94].

Rails, laid on the track, are checked for presence of stratifications and cracks in rail head, in neck, in base, and at bolt holes, and also for presence of defects of seam in weld joints. For this in the USSR and abroad there are created mobile installations (on carts or in special railroad cars), making it possible to carry out this check with great speed.

Check of bridge constructions (mainly weld joints) is also an example of effective application of ultrasonic methods of check on railroad transportation [287].

In riveted connections, operating in conditions of action of thermal and mechanical stresses and aggressive medium (for instance in boilers), there can be formed and developed characteristic cracks, partially hidden by heads of rivets. Ultrasonic echo-method can be used for detection of such cracks [288].

It is possible to cite still a great number of examples of possible use of ultrasonic methods for check of articles in operation.

It is also possible to cite many additional examples of effective check of various blanks and semifinished products in their production process; however, the given examples are absolutely sufficient in order to affirm that ultrasonic methods of check permit revealing a large part of defects appearing in metallic blanks and semifinished products at various stages of technology.

VIII

COMPARATIVE EVALUATION OF THE EFFECTIVENESS OF DIFFERENT METHODS OF NONDESTRUCTIVE TESTING

There is indubitable interest in evaluation of the revealability of different defects by one or another method of nondestructive testing, and also evaluation of the effectiveness of using different methods of nondestructive testing for detection of a defect of given type.

In Table 9 are given 70 forms of defects considered in Chapter I. In the first three columns of the table are given basic characteristics of the defects. In the fourth column is shown behavior of defect during further treatment and ways to correct the defect when possible. It is necessary to note that the determination "uncorrectable defect" is not always a basis for rejection of a part. The part should be rejected if under further treatment the defective zone does not depart and dimensions and quantity of defects exceed those permissible by technical conditions.

In the right part of table are enumerated methods of nondestructive testing and a five-point rating of the revealability of every defect by these methods. If the method is inapplicable, it is designated by zero. The highest appraisal of revealability is given only when the method can be used for manifestation of a defect of given form without limitations.

In the last column is given general characteristics of the revealability of every defect. These characteristics are in a fraction in the numerator of which is the highest point of revealability of this defect by whatever method, and in the denominator is the product of the number of methods which can be used by the average point for revealability of a defect by these methods.

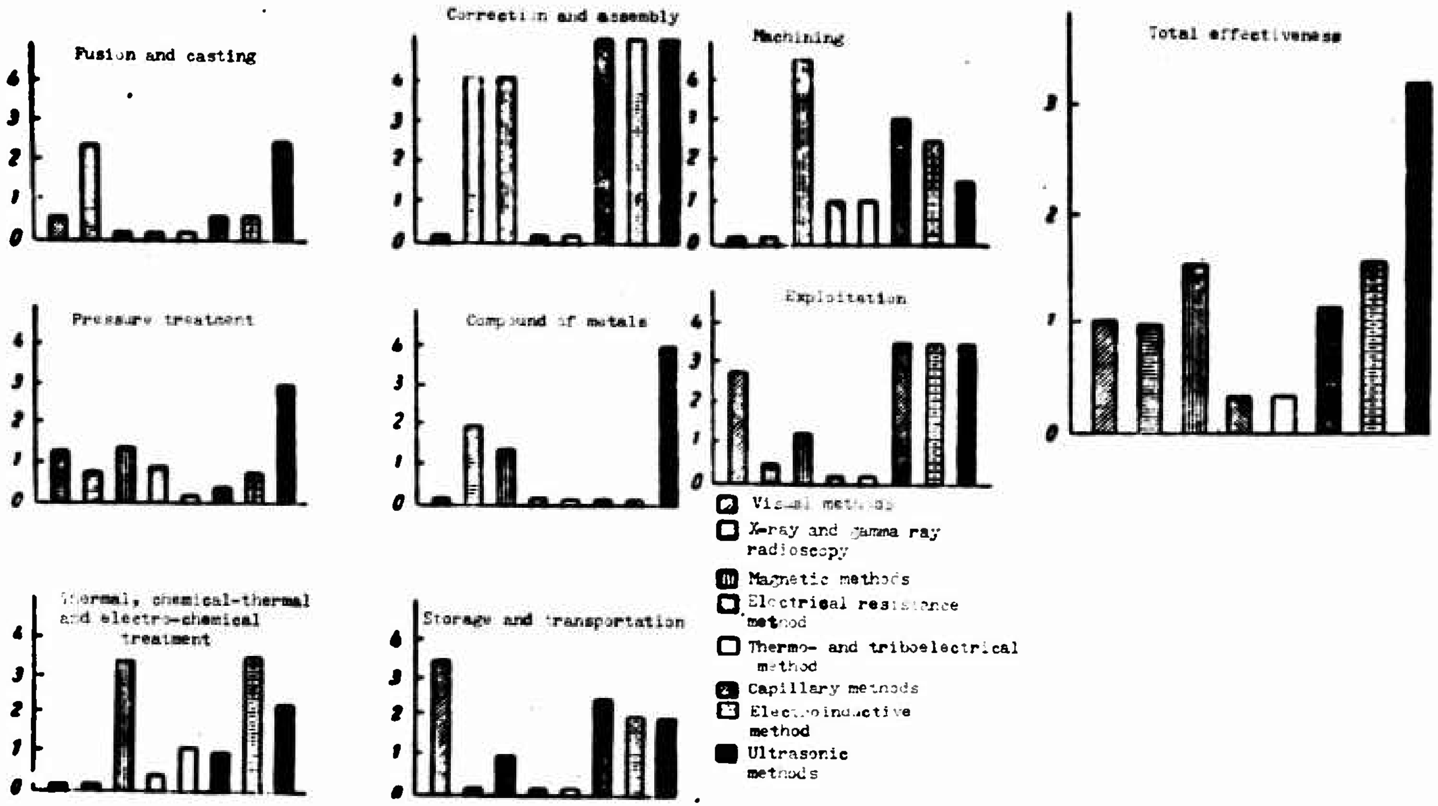

Fig. 284. Effectiveness of methods of nondestructive testing during detection of defects appearing at different stages of technological process and comparative total effectiveness (universality) of these methods.

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION.

Methods: В — Visual; РГ — X-Ray and Gamma Ray Radioscopy; М — Magnetic; ЭС — Electrical Resistance; ТЭ — Thermo- and Triboelectrical, Electrostatic; [To] (К) — Capillary; ЗИ — Electroinductive; УЗ — Ultrasonic.

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment;	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЭС	ТЭ	К	ЗИ	УЗ	
			Fusion and Casting									
1. Deviation from assigned composition.	Error in calculation of charge, incorrect metal, burning out of separate alloy components.	Non-correspondence of contents of alloy components to values shown in specifications.	Non-correctable defect.	0	0	0	0	1	0	0	0	$\frac{1}{1 \times 1}$
2. Non-metallic, slag, flux inclusions.	Bad purification of surface area of melt before casting, bad tapping of slag or flux during pouring, bad preparation of loam, incorrect molding.	Inclusions of products of deoxidation and refining and also slag, flux, particles of fireproof materials, graphite electrodes, casting loam, and others.	Incorrectable defect. During subsequent deformation are extruded into solid filaments or short lines, and depending upon their fragility, can be a seat of disturbance.	0	4	0	0	0	0	0	4	$\frac{4}{2 \times 4}$
3. Oxides, blisters, crusts.	Oxidized film in casting due to insufficiently thorough tapping before pouring or due to oxidation of metal by air trapped by the stream of metal during pouring.	Thin, usually hard and fragile layers disturbing continuity of metal.	Noncorrectable defect. During treatment the disturbance of continuity remains and can become a seat of disturbance.	0	0	0	0	0	2	2	3	$\frac{3}{3 \times 2.33}$
4. Unfused sections.	Interruption of stream in process of pouring, cold metal, short-run casting, insufficient metal-static pressure in casting, inaccurate slag shifter during pouring.	Thin layers, disturbing continuity of metal.	The same	2	1	0	0	0	0	2	3	$\frac{3}{4 \times 2}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION: (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment;	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
5. Shrinkage cavities.	Insufficient casting supply in crystallization, absence of conditions for directed crystallization.	Cavities of different magnitude and irregular shape with strongly oxidized deposits and nonmetallic inclusions.	Remainders of shrinkage cavity under treatment are not welded and are turned into different disturbances of continuity, lowering strength. Part of ingot containing shrinkage cavity therefore must be removed.	0	4	0	0	0	0	0	4	$\frac{4}{2 \times 4}$
6. Shrinkage pores.	Insufficient casting feed in the crystallization process.	Thin, well-developed interdendritic cavities, for the most part in axial zone of ingot.	Can not be welded in process of deformation and lead to formation of disturbance of continuity.	0	4	0	0	0	2	0	3	$\frac{4}{2 \times 3}$
7. Gas porosity.	Liberation of gases dissolved in the liquid metal with mobility of these gases in the crystallizing casting.	Scattered small gas pores over volume of ingot.	During pressure treatment frequently are welded.	0	4	0	0	0	0	0	3	$\frac{4}{2 \times 3.5}$
8. Blowholes.	Unification of gas pores liberated from the liquid metal into large pores with sufficient mobility in the crystallizing casting (for instance during delayed cooling).	Accumulations of gases, frequently concentrated beneath the crust of the ingot.	During pressure treatment core bubbles are welded; crust bubbles are pressed but are not welded (due to gas or oxide film). During heating the pressed bubble frequently is inflated and becomes exposed.	0	4	0	0	0	0	0	3	$\frac{4}{2 \times 3.5}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
9. Dendritic liquation	Rapid cooling of liquid alloy, crystallizing a considerable interval of temperatures.	Heterogeneity of chemical composition of alloy in volume of grain.	Can be in considerable degree removed by prolonged annealing (homogenization). Deformation of metal with noticeable dendritic liquation leads to formation of fibrous structure.	0	2	0	0	0	0	0	0	$\frac{2}{1 \times 2}$
10. Liquation with respect to specific gravity.	Bad mixing of melt before pouring, delayed crystallization.	Enrichment of lower part of casting by components with larger, specific gravity, and the upper part with smaller specific gravity.	Noncorrectable defect, leading to different behavior of various sections of ingot during further treatment.	0	2	0	0	0	0	0	0	$\frac{2}{1 \times 2}$
11. Zonal liquation	Displacement of liquid mother liquor enriched by fusible components in interdendritic space of the crystallized alloy skeleton, crystallizing in a considerable interval of temperatures.	Increased concentration of fusible components in central (direct) or in peripheral (reverse liquation) zones of ingot.	Homogenization does not remove liquation. Liquational deposits, oriented in accordance with deformation of metal can become the seat of damage.	0	2	0	0	0	0	0	0	$\frac{2}{1 \times 2}$
12. Hot cracks.	Destruction of crystallized alloy skeleton under thermal and shrinkage stresses at high temperatures (when elastic properties of alloy are low).	Cracks of intercrystalline character with strongly oxidized surfaces; when the volume of eutectic is larger the cavity of the crack usually is flooded by liquid eutectic.	Noncorrectable defect. During pressure treatment they lead to damage (for instance, to formation of "birdhouses"), since oxidized surfaces of cracks are not welded.	0	3	0	0	0	2	2	4	$\frac{4}{4 \times 2.75}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
13. Fins.	Breakthrough of liquid metal from inner zones to the surface through the external crystallized layers.	Fade-over on surface of ingot.	During pressure treatment are flattened, forming on the surface thin easily separable blisters.	4	0	0	0	0	0	0	0	$\frac{4}{1 \times 4}$
14. Cold cracks.	Destruction of casting under thermal and shrinkage stresses at relatively low temperatures when plasticity of alloy is small.	Cracks of transcrystalline character with light unoxidized surfaces.	Usually are welded during pressure treatment, in shaped castings can be corrected by auxillary welding.	2	3	0	0	0	2	2	4	$\frac{4}{5 \times 2.}$[illegible]
			Pressure Treatment									
15. Surface, internal cracks.	Unwelded cracks of ingot, considerable stresses in metal during deformation.	Separate cracks or a network of cracks at different depths or on the surface.	Noncorrectable defect.	2	2	2	2	0	2	2	4	$\frac{4}{7 \times 2.3}$
16. Stratifications	Unremoved and unwelded residues of shrinkage cavity or pores.	Internal disturbances of continuity oriented along direction of fiber.	Noncorrectable defect.	0	0	0	2	0	0	0	4	$\frac{4}{2 \times 3}$
17. Deformation stratifications	Different plasticity of oxidized blister and base metal (mainly in aluminum alloys).	Thin gaps between surface of oxidized blister and base metal.	Noncorrectable defect.	0	0	0	0	0	0	0	4	$\frac{4}{1 \times 4}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
18. Stratifications of longitudinal seam.	Non-observance of conditions of pressing of profiles with closed cross section of complicated form (incomplete welding of oxidized surfaces, formed during efflux).	Full or partial disturbance of continuity in planes where halves of profile section join.	Noncorrectable defect.	0	0	0	0	0	0	4	4	$\frac{4}{2 \times 4}$
19. Extrusion shrinkage cavities.	Outstripping of internal layers of extruded rod or profile during efflux.	Cavity in central zone of extruded rod near rear end.	Noncorrectable defect.	0	4	0	2	0	0	0	5	$\frac{5}{3 \times 3.66}$
20. Fissures.	Insufficient plasticity (non-correspondence of temperature and degree of deformation); nonuniform flow rate of internal and external layers of metal during extrusion.	Rough tears on edges of a rolled or on the surface of an extruded or drawn blank.	Noncorrectable defect.	5	0	0	0	0	0	0	0	$\frac{5}{1 \times 5}$
21. Internal breaks.	Non-correspondence of flow rate of internal layers of metal during extrusion or drawing; tensile stresses in internal layers of metal.	Rough damage in axial zone of extruded and drawn blanks; forging cracks in forgings of square cross section, oriented along diagonals of square.	Noncorrectable defect.	0	0	0	0	0	0	0	4	$\frac{4}{1 \times 4}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
22. "Bird-houses" [exact translation unknown].	Opening of thermal cracks or flacs in deformation under compressing stresses oriented along the interface.	Cavities of different dimensions and outlines with smoothed internal walls.	Noncorrectable defect.	2	4	0	0	0	0	0	4	$\frac{4}{3 \times 3.5}$
23. "Impediments."	Formation of flattened folds on surface of metal during forging.	Disturbance of continuity on surface of blank, penetrating to a shallow depth.	Noncorrectable defect.	2	0	2	0	0	2	0	3	$\frac{3}{4 \times 2.25}$
24. Settings.	Formation of pressed and rolled folds and burrs during rolling due to incorrect calibration of rollers.	The same.	Noncorrectable defect.	2	0	0	0	0	2	0	3	$\frac{3}{4 \times 2.25}$
25. Dents.	Impingement of outside solid particles on surface of hammer, striker stamp, or roller.	Local deepenings of different area.	Corrected by stripping, if dimension of blank do not go beyond the limits of minus allowance.	4	0	0	0	0	0	0	0	$\frac{4}{1 \times 4}$
26. "Graduation lines."	Impingement of outside solid particles on surface of matrix or mandrel.	Grooves of different depth, proceeding sometimes all along length of external or internal surface of an extruded or drawn blank.	The same.	4	0	0	0	0	0	0	0	$\frac{4}{1 \times 4}$
27. Various thickness (lamination).	Incorrect installation of rollers of rolling mill, change of gap in rolling process.	Deviation from nominal dimensions.	Noncorrectable defect.	0	0	3	3	0	0	3	5	$\frac{5}{4 \times 3.25}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
28. Varying wall thickness of pressed or pulled intermediate products in the cross section.	Misalignment in installation of needle of press or mounting of drawing machine with respect to matrix.	The same.	Noncorrectable defect	0	1	3	3	0	0	3	5	$\frac{5}{5 \times 3}$
29. The same, for pipes, shelves, profiles in the longitudinal direction.	Incorrect installation of needle of press or mandrel in longitudinal direction, irregularity of traction of drawing machine.	Deviation from nominal dimensions (in particular, in pipes and profiles of variable cross section).	Noncorrectable defect.	0	1	3	3	0	0	3	5	$\frac{5}{5 \times 3}$
30. Hairline cracks.	Deformation of blowholes, nonmetallic inclusions.	Thin strokes on surface and at different depths (revealed during step machining) of blanks.	Noncorrectable defect. In loaded zones can become focus of damage.	0	0	5	0	0	0	0	0	$\frac{5}{1 \times 5}$
31. Scales.	Deformations of fins and drops adhering to surface of ingot.	Thin, rolled or drawn films, densely adjacent to surface of metal (easily separated).	Removed by stripping of surface of blank.	3	0	0	0	0	0	0	0	$\frac{3}{1 \times 3}$
32. Flocs.	Increased hydrogen content.	Thin winding cracks, in breaklight round spots ("flakes"), frequently oriented in the direction of liquational deposits in cross section of forged blank.	Noncorrectable defect, especially dangerous for important articles, since in deformation flocs can be welded and then form again.	0	0	4	0	0	0	0	4	$\frac{4}{2 \times 4}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristics of revealability
				В	РГ	М	ЭС	ТЗ	К	ЗИ	УЗ	
Thermal, Chemical-Thermal, and Electrochemical Treatment												
33. Coarse-grained structure.	Exceeding assigned heating temperature during heat treatment.	Coarse-grained structure, revealed in break of metal or on etched slide.	Can be corrected by heat treatment (for instance, normalization).	0	0	3	0	0	0	3	3	3 / 3 × 3
34. Overheating.	The same, but to a larger degree.	Coarse-grained structure, oxide and sulfide deposits along boundaries of grains (in steel).	In certain cases is corrected by complicated treatment.	0	0	3	0	0	0	3	3	3 / 3 × 3
35. Overburning.	The same but in still larger degree.	Coarse-grained structure, fusion of deposits along boundaries of grains.	Noncorrectable defect.	0	0	3	0	0	0	3	3	3 / 3 × 3
36. Noncorrespondence to assigned structure.	Incorrect conditions of heating or cooling during heat treatment.	Structure and property do not correspond to assigned.	Corrected by additional heat treatment.	0	0	3	0	0	0	4	0	4 / 3 × 3.3
37. Soft spots.	Insufficient heating before hardening or insufficiently intense cooling of sections of surface.	On surface of hardened part sections with lowered hardness.	Corrected by repeated heat treatment.	0	0	0	0	3	0	4	0	4 / 2 × 3.5
38. Thermal cracks (including tempering).	Sharp heating or cooling (for instance, during hardening); nonuniform change of volume due to form of article; inclination of alloy to crack formation.	Single or grouped thin cracks, starting on surface and spreading to different depths.	Noncorrectable defect.	0	0	4	0	0	4	4	4	4 / 4 × 4

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
39. Noncorrespondence of thickness of tempered layer during treatment by TVCh [high frequency current].	Incorrect conditions of high-frequency hardening.	Incorrect distribution of properties and structural components along the cross section.	Corrected by repeated heat treatment.	0	0	4	0	3	0	4	4	$\frac{4}{4 \times 3.75}$
40. Decarbonization.	Heating of steel articles in an atmosphere containing water vapor, carbon dioxide, or hydrogen.	Burning out of carbon in surface layers, leading in a number of cases to lowering the strength of steel.	Noncorrectable defect.	0	0	4	0	3	0	4	0	$\frac{4}{3 \times 3.66}$
41. Carburization.	Heating of steel articles in an atmosphere of excess carbon monoxide.	Saturation of surface layers by carbon, increasing fragility and inclination to crack formation.	Noncorrectable defect.	0	0	4	0	3	0	4	0	$\frac{4}{3 \times 3.66}$
42. Scaling cracks.	Change of sign of voltage in thin surface layer (for instance, in polishing a hardened article.	Sealing of surface layer of steel part.	Noncorrectable defect.	0	0	3	0	0	3	0	4	$\frac{4}{3 \times 3.36}$
43. Tempering microcracks.	Brittle rupture, for instance, in martensite needles under stresses of the second kind.	Internal microcracks, frequently along boundaries of formerly big grains of austenite.	Noncorrectable defect.	0	0	0	1	0	3	0	1	$\frac{3}{3 \times 1}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	Н	ЗИ	УЗ	
44. Hydrogen cracks.	Saturation of surface layer of steel by hydrogen under the action of alkalis and acids.	Surface thin cracks on parts not subjected to dehydrogenating tempering.	Noncorrectable defect.	0	0	5	0	0	5	5	5	$\frac{5}{4 \times 5}$
45. Noncorrespondence of thickness of cemented, nitrated, oxidized, and other layers.	Disturbance of conditions of chemical-thermal and electrochemical treatment (change of rate of diffusion processes).	Change of depth of cementation, nitration, oxidizing, appearing in change of hardness of fatigue and anticorrosive characteristics.	Noncorrectable defect.	0	0	3	2	3	0	4	3	$\frac{3}{5 \times 3}$
46. The same, for galvanic plating.	Nonuniform distribution of current intensity due to complexity of form of part, disturbance of conditions of treatment.	Nonuniform distribution of metal of protective coating along surface of part.	Noncorrectable defect.	0	0	4	0	0	0	4	0	$\frac{[illegible]}{2 \times 4}$
			Machining									
47. Finishing cracks.	Destruction of metal in surface layer, cold hardened during finishing operations.	Surface microcracks, developed subsequently during work of the part under a load (especially at increased temperature).	In certain cases is corrected by removal of surface layer by electrolytic polishing.	0	0	4	0	0	4	4	4	$\frac{4}{4 \times 4}$
48. Burns.	Sharp heating of separate sections of surface during grinding of a steel part.	Hardened sections of small area.	Noncorrectable defect. Can be focus of damage.	0	0	5	3	3	0	3	0	$\frac{5}{4 \times 3.75}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
49. Polishing cracks.	Sharp heating of surface layer of steel article during grinding.	Netword of thin cracks on surface of part.	Noncorrectable defect.	0	0	5	0	0	5	0	0	$\frac{5}{2 \times 5}$
			Correction, Assembling									
50. Straightening, assembly cracks.	Appearance of considerable stresses during assembly or correction of warped parts.	Surface cracks (across direction of maximum tensile stresses applied during assembly or correction).	Noncorrectable defect.	0	4	4	0	0	5	5	5	$\frac{5}{5 \times 4.6}$
		Compound of Metals (Welding, Soldering, Riveting, Gluing)										
51. Coarse-granularity around the seam area.	Overheating of metal during welding – in the zone adjacent to the seam.	Large grain in zone of thermal influence, lowering strength.	Noncorrectable defect.	0	0	0	0	0	0	0	4	$\frac{4}{1 \times 4}$
52. Metallurgical defects of welded seam.	Incorrect welding.	Disturbances of continuity: cavities pores and slag inclusions in seam.	Noncorrectable defect.	0	4	3	0	0	0	0	4	$\frac{4}{3 \times 3.7}$
53. Nonfusion.	Disturbance of conditions of welding.	Absence of welding in part of cross section of seam.	In a number of cases can be corrected by "auxillary welding."	0	3	3	0	0	0	0	4	$\frac{4}{3 \times 3.33}$
54. Welding cracks.	Action of thermal and structural stresses during cooling of welded joint.	Cracks in seam or on boundary of zone of thermal influence.	In separate cases for unimportant articles is corrected by auxillary welding, preparing the defective place and drilling ends of cracks.	0	4	3	0	0	0	0	5	$\frac{5}{3 \times 4}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
55. Cracks in rivet connections.	Considerable stresses in the cold hardening.	Cracks in body of rivet or zone of base metal adjoining rivet.	Noncorrectable defect.	0	3	2	0	0	0	0	4	$\frac{4}{3 \times 3}$
56. Unsoldered area.	Insufficiently thorough purification of soldered surfaces or disturbance of temperature regime of soldering.	Unsoldered sections.	Noncorrectable defect.	0	3	0	0	0	0	0	4	$\frac{4}{2 \times 3.5}$
57. Unglued area.	Insufficiently thorough purification of glued surfaces or disturbance of temperature regime of bonding.	Unglued sections.	Noncorrectable defect.	0	0	0	0	0	0	0	4	$\frac{4}{1 \times 4}$
58. Disturbance of diffusion cohesion.	Insufficiently thorough preparation of surfaces, disturbance of temperature regime.	Sections in which there is no cohesion.	Noncorrectable defect.	0	0	0	0	0	0	0	4	$\frac{4}{1 \times 4}$
59. Mechanical surface damage.	Incorrect stacking, impacts, scratching, friction of intermediate products and articles against each other.	Nicks, dents, lines, scratches, damage to protective coatings of plating layer.	In a number of cases can be corrected by stripping, if overall dimensions of blank do not go beyond allowance limits.	4	0	0	0	0	0	0	0	$\frac{4}{1 \times 4}$
60. Atmospheric surface corrosion.	Destruction of surface under the action of a humid atmosphere.	Damage of metal over whole surface (uniform corrosion), or on separate sections (pitting).	The same.	4	0	0	0	0	4	0	0	$\frac{4}{2 \times 4}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
61. Atmospheric intercrystallite corrosion.	Destruction of metal under the action of a humid atmosphere, spreading chiefly along boundaries of grains.	Losses of metallic properties in zone of corrosive damage.	Noncorrectable defect.	3	0	0	0	0	3	4	4	$\frac{4}{4 \times 3.5}$
62. Cracking during storage.	Action of residual stresses (thermal and mechanical), especially under the influence of a moist or agressive medium.	Thin surface cracks appearing usually in zones of concentration of stresses.	Noncorrectable defect.	3	0	4	0	0	4	4	4	$\frac{4}{5 \times 3.8}$
Exploitation												
63. Fatigue cracks.	Brittle rupture, chiefly in zone of stress concentrators under the action of multiple loads.	Thin surface or interval cracks developed as the part works, passing usually along grain.	Noncorrectable defect.	3	3	4	0	0	4	4	4	$\frac{4}{6 \times 3.67}$
64. Thermal fatigue cracks.	Brittle rupture under the action of multiple temperature fluctuations of considerable amplitude (especially during simultaneous application of mechanical loads).	Thin surface cracks, appearing near boundary of zones of different temperature or in a zone of concentration of stresses developed during work of part and passing in the beginning along boundaries of grains, and as they develop along the grain.	Noncorrectable defect.	3	0	0	0	0	4	4	4	$\frac{4}{4 \times 3.75}$

TABLE 9. BASIC FORMS OF DEFECTS OF METAL AND METHODS OF THEIR NONDESTRUCTIVE DETECTION. (Cont'd)

Form	Causes of formation	Brief characteristics	Influence on quality of blank; behavior in further treatment	Revealability by methods of nondestructive control								General characteristic of revealability
				В	РГ	М	ЗС	ТЗ	К	ЗИ	УЗ	
65. Creep cracks.	Prolonged influence of mechanical stresses.	Thin cracks appearing on surface in zones of concentration of stresses developed during work of part, and passing frequently along boundaries of grains.	Noncorrectable defect.	3	0	3	0	0	4	4	4	$\frac{4}{3 \times 3.6}$
66. Contact cracks.	Contact with molten metals (melted solder or antifriction alloys).	Surface cracks appearing in loaded parts.	Noncorrectable defect.	3	0	3	0	0	0	3	3	$\frac{3}{4 \times 3}$
67. Surface corrosion.	Action of aggressive media.	Damage of the whole surface (uniform corrosion) or separate sections (pitting).	In certain cases is corrected by stripping, if overall dimensions of part do not go beyond the limits of allowance.	3	0	0	0	0	4	0	0	$\frac{4}{2 \times 3.5}$
68. Intercrystallite corrosion.	Action of aggressive media, spreading chiefly along boundaries of grains.	Destruction of metal, losses of metallic properties in zone of damage.	Noncorrectable defect.	3	0	0	0	0	4	4	4	$\frac{4}{4 \times 3.75}$
69. Gas high-temperature corrosion.	Action of aggressive gases, chiefly at high temperature.	Cracks developing from surface in heated zones and passing usually along grain boundaries.	Noncorrectable defect.	3	0	0	0	0	4	4	4	$\frac{4}{4 \times 3.75}$
70. Corrosion cracking under stress.	Simultaneous influence of aggressive medium and mechanical stresses.	Cracks in brass articles, rivet seams, boiler drums, and others, developed in exploitation.	Noncorrectable defect.	0	0	0	0	0	4	4	4	$\frac{4}{3 \times 4}$

Thus, reliability of detection of defect is characterized by value of numerator, and the possibility of using several methods — by the first co-factor of the denominator.

The total of points for each method given in the table, calculated for all defects met on a given stage of the technological process and divided by the number of these defects gives a coefficient which can serve as a sufficiently objective characteristic of the effectiveness of the method of control for manifestation of this group of defects. In Fig. 284 (cf. p.378) these coefficients are given.

Diagrams show that effectiveness of every method changes from stage to stage, which is fully explicable, inasmuch as every method most reliably reveals defects of a defined character.

Ultrasonic methods, as diagrams show, in most cases give best results, which indicates great universality as compared to other methods. Universality of ultrasonic methods follows from the considerable variety of variable adjustable parameters, used by these methods.

The sum of points for every method, calculated for all enumerated defects in Table 9 and divided by the total number can serve as a sufficiently objective characteristic of universality of the method of nondestructive control.

With such appraisal the visual method, method of X-ray and gamma ray radioscopy and capillary methods are characterized by a coefficient close to one; methods of electrical resistance, thermo- and triboelectrical and also electrostatic ~0.3; magnetic and electroinductive methods ~1.6. Ultrasonic methods have the highest coefficient of universality (>2.7).

This is confirmed by Soviet and foreign practice: with each day, effective use of methods of ultrasonic defectoscopy in the People's economy is expanded their share in subjects of meetings and conferences on nondestructive methods of testing increases the number of laboratories conducting methodical developments grows, as does the literature dedicated to ultrasonic defectoscopy [76, 106, 120, 121, 133, 137, 157, 162, 164, 180, 187, 191, 193, 198, 202, 228, 229, 233, 236, 237, 242, 244, 247, 270, 284, 291-307].

It is assured that universality of ultrasonic methods of control will increase with further development and improvement of methodology and equipment.

The use of different forms of elastic oscillations in complicated multichannel

installations supplied with follow-up systems, indicators, analog computers and recorders will make possible highly productive control of articles of complicated form in conditions of continuous production. This will allow to detection of defects of different character, location and orientation, determination of dimensions of these defects, rejection of controlled articles, and a record of test results.

Thus, ultrasonic defectoscopy will be turned into defectometry and defectography.

Still large effect can be obtained from ultrasonic methods of control with a reasonable combination with other methods, first, with electroinductive methods. Creation of flaw detectors "combines" and application of complex defectoscopy will absolutely allow a solution to the most complicated problems appearing in the control of different articles.

For a solution of such problems it is necessary not only to develop and to improve methodology and equipment, it is necessary also that designers and technologists consider specific requirements of defectoscopy.

Just as with complication of constructions of machines, aggregates and form of blanks it became necessary to introduce requirements of productibility in order to ensure reliable quality control of blanks and articles so now it is necessary to introduce requirements of flaw detection of blanks, parts, aggregates and machines. This signifies, for instance, that in the most responsible sections of blanks (for instance, stamping) there must be provided flat sites convenient for control; in ready constructions, access to important sections for control in exploitation, etc., should be possible.

In separate cases, this can lead to increase of weight of blank and to complication of construction, however these inconveniences will be compensated by increase of operational reliability of parts and the whole construction and this is the most important creation of complicated and responsible constructions, designed for work in especially severe exploitational conditions.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log